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VESTIGATION OF THE NATURAL MICROSCALE
ANISMS THAT CAUSE VOLUME CHANGE IN
EXPANSIVE CLAYS

DEPARTMENT OF TRANSPORTATION ★ UNITED STATES OF AMERICA ★

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16. Abstract

The report concludes a study of the natural microscale mechanisms which cause volume change in expansive soils. The mechanisms were defined and attempts were made to delineate the roles of the mechanisms in the volume change process by inferring the respective influence from observed physical, physicochemical, and mineralogical data. The three major microscale mechanisms which cause the volume change are clay particle attraction, cation hydration, and osmotic repulsion. These three major mechanisms can be represented by the total soil suction which is composed of two components, matrix and osmotic. The matrix component represents the clay particle attraction and cation hydration mechanisms. The osmotic component represents the osmotic repulsion mechanism. The results of the laboratory study concluded that although interesting trends may be inferred using the approach, it is not successful to infer microscale behavior from macroscale observations. For the materials and range of moisture contents tested it was concluded that the clay particle attraction and cation hydration mechanisms play the major role in causing volume change. At higher moisture contents and higher cation concentration environments the osmotic repulsion mechanism provides a secondary influence on volume change. The thermocouple psychrometric technique was shown to be a simple, quick, and reliable method for evaluating soil suction.

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PREFACE

The study of the methodology for prediction and minimization of detrimental volume change of expansive soils in highway subgrades is a 4-year investigation funded by the U. S. Department of Transportation, Federal Highway Administration, under Intra-Government Purchase Order No. 4-1-0195, Work Unit No. FCP 34D1-132.

The work was initiated during June 1974 by the Soils and Pavements Laboratory (S&PL) of the U. S. Army Engineer Waterways Experiment Station (WES). Dr. Donald R. Snethen, Research Group, Soil Mechanics Division (SMD), S&PL, was the principal investigator during the period of this report. The work reported herein was performed by Dr. Snethen and Dr. Lawrence D. Johnson, Research Group, SMD, and Dr. David M. Patrick, Engineering Geology Research Facility, Engineering Geology and Rock Mechanics Division, S&PL. The report was prepared by Drs. Snethen, Johnson, and Patrick. The investigation was accomplished under the general supervision of Mr. Clifford L. McAnear, Chief, SMD, and Mr. James P. Sale, Chief, S&PL.

Directors of WES during the conduct of this portion of the study and preparation of the report were COL G. H. Hilt, CE, and COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
angstroms	0.001	micrometres
inches	2.54	centimetres
feet	0.3048	metres
pounds (mass)	0.4535924	kilograms
gallons (U. S. liquid)	3.785412	cubic decimetres
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
tons (force) per square foot	95.76052	kilopascals
atmospheres (technical = 1 kgf/cm^2)	98.0665	kilopascals
atmospheres (normal = 760 torr)	101.325	kilopascals

AN INVESTIGATION OF THE NATURAL MICROSCALE MECHANISMS THAT CAUSE VOLUME CHANGE IN EXPANSIVE CLAYS

INTRODUCTION

1. The purpose of this research task was to define and verify the natural microscale mechanisms that cause volume change in expansive soils. Since no direct methods are readily available to measure these microscale forces, their verification involved an inference of microscale mechanism influence from observed macroscale volume change behavior. The report concludes this phase of the overall study and provides definitions of the major microscale mechanisms, definitive discussions on the soil suction concept, descriptions of soil suction evaluation procedures, and the results of an extensive laboratory study to obtain data for the macroscale behavior characteristics. Evaluation and verification of identification/classification and testing/prediction techniques from the standpoint of microscale mechanisms and correlations between measured properties and volume change characteristics are beyond the scope of this investigation and will be discussed in detail in two subsequent interim reports.

REVIEW OF MICROSCALE MECHANISMS

2. In a previous report[1] the physical and physicochemical properties which influence volume change were defined and described in some detail. Of the properties discussed, one, the soil composition (amount and type of clay mineral), determines the potential for volume change. The remaining intrinsic properties and ambient environmental conditions determine the magnitude and rate of volume change. The volume change phenomenon is the result of sorption of water (adsorption for expansion, desorption for shrinkage) onto the surface and into interlayer positions of active clay minerals.

3. In an attempt to better understand the volume change phenomenon, an effort was made to isolate the microscale mechanisms which cause the sorption of water in expansive soils. Based on the literature review and the understanding of the U. S. Army Engineer Waterways Experiment Station (WES) research team at that time, the microscale mechanisms defined and described in Table 1[1] were considered to be the basic mechanisms or driving forces causing the volume change. Since that time, a more detailed knowledge of the mechanisms has been developed, as explained in the following paragraphs.

4. Basically, the expansive soils that most State Highway Agencies deal with are good foundation materials, provided changes in the ambient conditions do not cause a change in the availability of water to the material. For expansive materials to expand, three criteria must be satisfied, namely (a) an available source of water, (b) a driving force to move the water, and (c) a mechanism or group of mechanisms which actually cause the volume change. Both the sources of water and modes of moisture transfer were discussed in some detail in Reference 1. With this in mind, the discussion here will concentrate on verifying the microscale mechanisms causing volume change. Of the six mechanisms listed in Table 1, three are not microscale phenomena, namely capillary imbibition, Van der Waal forces, and elastic relaxation.

5. Capillary imbibition listed in Table 1 as a mechanism is not

Table 1

Natural Microscale Mechanisms Causing Volume Change in Expansive Soils

Mechanism	Explanation	Influence on Volume Change
Osmotic repulsion	Pressure gradients developed in the double-layer water due to variations in the ionic concentration in the double layer. The greatest concentration occurs near the clay particle and decreases outward to the boundary of the double layer	The double-layer boundary acts as an osmotic membrane when exposed to an external source of free water; that is, it tries to draw the water into the double layer to reduce the ionic concentration. The result is an increase in the double-layer water volume and the development of repulsive forces between interacting double layers. The net result is an increase in the volume of the soil mass
Clay particle attraction	Clay particles possess a net negative charge on their surfaces and edges which result in attractive forces for various cations and in particular for dipolar molecules such as water. This makes up the major "holding" force for the double-layer water	In an effort to satisfy the charge imbalance, the volume of water in the double layer will continue to increase until a volume change of the soil mass occurs
Cation hydration	The physical hydration of cations substituted into or attached to the clay particle	As the cations hydrate, their ionic radii increase, resulting in a net volume change of the soil mass
London-van der Waal forces	Secondary valence forces arising from the interlocking of electrical fields of molecule associated with movements of electrons in their orbits. The phenomenon frequents molecules in which the electron shells are not completely filled	The interlocking of electrical fields causes a charge imbalance which creates an attractive force for molecules such as water
Capillary imbibition	Movement of water into a mass of clay particles resulting from surface tension effects of water and air mixtures in the pores of the clay mass. Compressive forces are applied to the clay particles by the menisci of the water in the pores	As free water becomes available to the clay mass, the pore water menisci begin to enlarge and the compressive forces are relaxed. The capillary film will enlarge and result in a volume change or supply water for one of the other mechanisms
Elastic relaxation	A readjustment of clay particles due to some change in the diagenetic factors	Volume change results from particle reorientation and/or changes in soil structure due to changes in the diagenetic factors

really a microscale mechanism in the sense of physically causing expansion. Instead, it is actually one of the modes of moisture transfer and, as such, provides a source of water for the true mechanisms. Capillary imbibition will influence both the magnitude and rate of volume change, but has little direct bearing on the sorption process and will not be considered further in these discussions.

6. Van der Waal forces, including London forces and hydrogen bonding, are weak attractive electrical forces which develop on the surfaces of clay minerals. These forces exist between adjacent clay mineral surfaces and tend to bond the surfaces together. An example of this kind of bonding can be observed in the coarse-grained micas in which thin sheets can be cleaved from the material. Similar forces occur in clay minerals except that the small particle size and large surface area of clays result in these forces being somewhat more important. The forces are in effect in both the dry and wet conditions and control the sorption of water. After sorption begins, the forces play a small part in bonding the water molecules to the clay surfaces. Van der Waal forces include three types of weak electrical attractive forces, namely:

a. Dipole-dipole attraction. These forces develop between polar molecules having permanent moments and are at least partly responsible for the orientation of water molecules and their bonding to the clay mineral surface.

b. Induction effects. These forces are similar to dipole-dipole attraction and occur between polar molecules; however, the induction effects occur between unoriented molecules by the interaction between one dipole and the polarized electrons of another dipole.

c. London forces. These forces, which are also termed "dispersive" forces, occur in all molecules or extremely small particles including nonpolar (zero dipole moment) varieties. The forces originate from the development of an instantaneous, nonpermanent dipole moment between two particles as they come into close proximity to one another. Under conditions where water is attracted to the clay mineral, the influence of Van der Waal forces is rapidly overcome by the

development of the double-layer water. In addition, this phenomenon is very hard to measure and interpret physically and, in cases where it can be evaluated, provides little or no practical information for the engineer. Accordingly this phenomenon is also dismissed.

7. Elastic release could actually be considered a special type of volume change rather than a cause of it since it is a particle reorientation resulting from swelling or unloading. Other factors such as diagenetic bonding and cementation significantly influence elastic release, generally on the side of volume change reduction. On the other hand, elastic release will influence capillary imbibition, one of the modes of moisture transfer, since particle reorientation will generally result in increased pore sizes.

8. The preceding discussions have effectively reduced the number of microscale mechanisms responsible for volume change to three: clay particle attraction, cation hydration, and osmotic repulsion. Several attempts have been made to isolate and verify the mechanisms of volume change and, in most cases, these three mechanisms are given primary responsibility for expansion.

9. In a study of swelling of compacted clays, Ladd[2] concluded that for samples compacted wet of optimum water content, swelling is caused by osmotic repulsive pressures, and for samples compacted dry of optimum, swelling is influenced by factors in addition to osmotic pressures. These factors include cation hydration and attraction of the clay particle surface for water, London-Van der Waal forces, elastic rebound, particle orientation, and presence of air. Ladd admitted that the relative importance of the additional factors was not known. An interesting point about Ladd's work is that, in a very general sense, he was pointing out a type of categorization of the range of applicability of the basic mechanisms. In other words, his concept of osmotic repulsion controlling volume change above optimum water content and cation hydration and clay particle attraction plus the other less significant factors having greater influence below optimum water content was a major step toward a better understanding of the volume change phenomenon.

10. Low[3] described five possible mechanisms of soil-water interaction which would, in turn, influence volume change behavior. These include hydrogen bonding, hydration of exchangeable cations, attraction by osmosis, dipole attraction, and Van der Waal forces. Hydrogen bonding and dipole attraction are specific terms for the clay particle attraction bonding forces and thus correspond to the clay particle attraction mechanism. Attraction by osmosis is the complementary term to osmotic repulsion. In other words, the mechanism of volume change is repulsion, but the repulsion is the result of osmotic attraction of water into the influence of the double-layer water.

11. Additional references concerning the role of mechanisms may be consulted--Ingles,[4,5] Quirk,[6] and Low[7]--and the results will be the same. That is, the three basic microscale mechanisms will be discussed along with a few relatively inconsequential mechanisms such as Van der Waal forces.

Definition of Mechanisms

12. Previous discussions have indicated that, at the microscale level, the mechanisms which cause volume change in expansive soils are clay particle attraction, cation hydration, and osmotic repulsion. In reality, the individual influence of each of these mechanisms is hard, if not impossible to separate from its counterparts. However, to adequately define the mechanisms, their individual roles will first be discussed, and then in summary, the interrelationships of the mechanisms will be addressed.

Clay particle attraction

13. Surface attractive relationships which exist between clay minerals, between clay minerals and water, and between clay minerals and cations are a result of the shape and internal crystallographic structure of the clay mineral. Clay minerals occur as tiny platelets having two types of exposed surfaces--edges and faces. The edges are generally more irregular in shape, exhibit a smaller surface area, and possess both positive and negative charges which are primarily due to broken bonds. The faces are generally flat, exhibit the majority of

the particles' surface area, and, in the case of smectites and illites, possess an electron-rich surface and negative charge due to the presence of oxygen atoms in the tetrahedral layer. The magnitude of these electrostatic charges and the resulting attractive forces is intensified because of the extremely small size of the clay mineral platelets. The smectites, particularly montmorillonite, are characterized by the substitution of divalent magnesium for trivalent aluminum in the octahedral layer. The substitution results in a net negative charge imbalance which may be satisfied by cations situated on interlayer positions (faces) and to a lesser extent on the platelet edges. The process of attracting and holding water molecules is achieved through the processes of hydrogen bonding of the water molecules to the clay mineral surface and dipole-dipole attraction of the water molecules for one another. A schematic representation of the process is shown in Figure 1a. Because the clay mineral surfaces are usually composed of either exposed oxygens or hydroxyls on faces and/or other positively charged ions on edges the hydrogen bonds may develop by either the oxygens attracting and bonding with the positive side of the dipolar water molecule or the hydroxyls attracting and bonding with the negative side of the water molecule. The hydrogen bonding of water molecules to the clay mineral surface provides the basic building blocks for the double-layer water which, in reality, is the moving force in soil expansion.

14. Charged surface-dipole attraction in soils involves the surface attractive forces discussed in the previous paragraph; however, the influence of these forces decreases with distance from the clay mineral surface. Water is a dipolar substance, that is, it has two centers of charge--one positive and one negative. To form an analogy,[8] the clay mineral surfaces (interior or exterior between particles) are analogous to negatively charged condenser plates with an electric field strength that decreases with distance from the surface. Water dipoles can orient themselves with their positive poles directed toward the negative surfaces with the degree of orientation decreasing with distance. The only flaw in this analogy is that at the midpoint between the plates or clay minerals, there would be a structural disorder

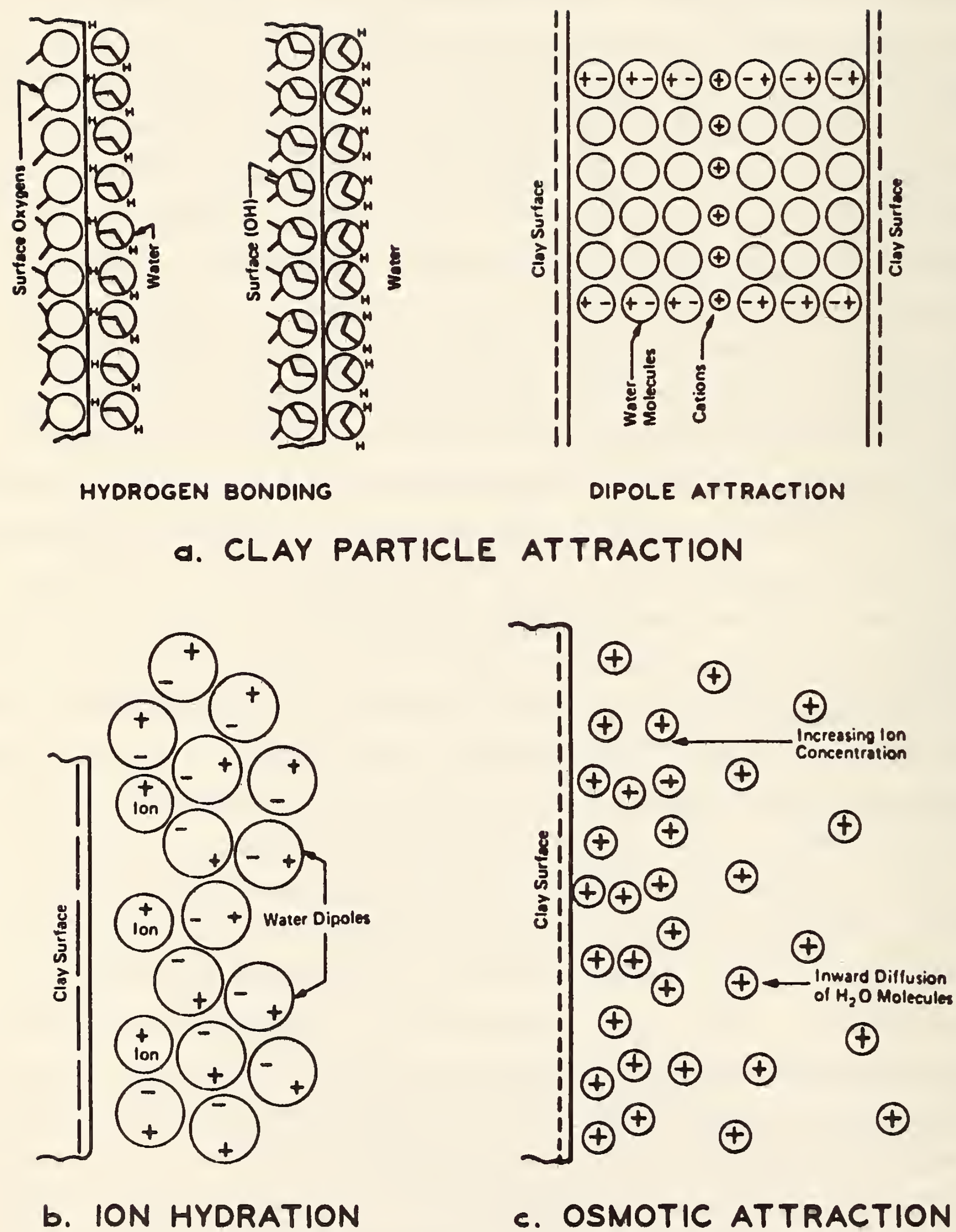

Figure 1. Mechanisms of water adsorption by clay surfaces (from Mitchell[8])

because like poles would be adjacent to one another. Ingles[5] suggests that this may not be far from correct because due to the high hydration number and energy of aluminum in the clay structure, water can be strongly attracted to the surfaces and interposes itself between the surfaces and the counterions, thus removing the counterion as far away as possible or, more precisely, to the midpoint. Such a configuration is shown at the right side of Figure 1a.

Cation hydration

15. The cation hydration mechanism is more easily understood if it is considered as a special case of the clay particle attraction previously discussed. Instead of the clay particles being surrounded by water molecules to balance the negative charge deficiency, suppose that cations such as calcium, magnesium, sodium, or potassium are attracted to the clay surface, rendering it neutral from a charge deficiency sense. There still exists a considerable force for the attraction of water in the form of hydration of the cations. This results from the charge of the cation not being fully neutralized. The influence of cation hydration involves both attraction force for water molecules, Figure 1b, and a physical increase in size (ionic radii) following hydration. In reality there are no purely clay-water or clay-cation systems; rather there is generally a clay-water-cation combination which gives rise to the third and final microscale mechanism, osmotic repulsion.

Osmotic repulsion

16. As explained earlier, the holding (electrostatic attractive) forces for water molecules and ions are greatest at the clay mineral surface and decrease with distance from the surface. Therefore, the concentration of cations will be greatest at the clay mineral surface and decrease with distance from the surface. When the soil-water-cation combination is exposed to a pore fluid having a different (lesser) ion concentration, the double-layer water acts as a semipermeable membrane allowing water to enter in order to bring the two differing ion concentrations into balance. This is generally denoted as osmotic attraction, Figure 1c. The result of the osmotic attraction is a

buildup of the double-layer water. The net result of the double-layer water buildup will be volume change (increase) of the soil mass. The precise influence of osmotic repulsion on volume change is not well understood; however, it is generally accepted that the mechanism has its greatest influence at higher moisture contents (i.e., at greater than optimum moisture content for compacted soils).

17. The previous discussions have been directed toward explaining the microscale mechanisms and their influence on volume change from the standpoint that they act individually. In reality, the three major mechanisms do not act individually; instead, they are quite dependent upon one another. For example, the sorption process cannot begin without clay particle attraction. Ion hydration cannot be significant without clay particle attraction and osmotic repulsion cannot influence volume change without the particle attraction for water and cations and the variation of cations within close proximity to the clay mineral. The importance of the interdependence is most evident when attempts are made to isolate and verify the direct influence of the individual mechanisms. Even the most sophisticated soil chemical analysis procedures do not provide the needed practical information to relate the mechanisms to volume change behavior. To overcome these deficiencies in available information, the engineer recognizes their existence and then measures the final result (volume change). The soil scientist's end result measurement involves the soil's affinity for water (soil suction). A combination of the two approaches is the basis of this research program; however, the need exists for a better definition of the terminology used by the soil scientist faction, which is included in the following paragraphs.

Definition of Soil Suction

18. Soil suction is a quantity that can be used to characterize the effect of moisture on the volume and strength properties of soils[9-12]; that is, soil suction quantitatively describes the interaction between soil particles and water, which determines the physical

behavior of the soil mass. Total soil suction is the force which is responsible for soil water retention. Suction is a pressure term which is a measure of the pulling force (tension) exerted on the water. Tension is also a term used to indicate the force of soil water retention and can be used interchangeably with suction; however, soil moisture suction or simply suction is generally preferred.

19. The total soil suction may be alternatively defined as the free energy present in soil water with respect to a pool of pure water located outside of the soil at the same elevation. This energy is the source of work that is done when the pool of pure water comes in contact with the soil. At equilibrium following contact with the pure water, the free energy is dissipated in the form of work that is done to pull the pure water into the soil, counter the friction, and expand the soil lattice. The effect that the dissipation of free energy or total suction has on the physical properties of the soil depends on the soil composition (type and amount of clay mineral) and the cation environment of the soil.

20. The total soil suction is the sum of the matrix and osmotic components. The matrix suction is comprised of the surface attractive forces for water and cations and the surface tension effects of water in soil, thus representing two of the three major mechanisms. The matrix suction is both water content and surcharge pressure dependent. The osmotic suction arises from the presence of soluble salts in the soil water and is identical in context with the osmotic attractive forces previously described. The osmotic suction will cause a physical change in the soil when contact is made with free water, provided the type and concentration of the salts in the soil differ from that of the free water. Osmotic suction is independent of water content and surcharge pressure.

Evaluation of Soil Suction

21. All processes and chemical reactions of which the natural microscale mechanisms are a part use energy. Evaluation of soil

suction is essentially an evaluation of the level of energy available to the natural microscale mechanisms that cause soil volume change. Changes in soil suction reflect the amount of energy in the pore water of the soil used by the mechanisms to cause swell.

Approaches

22. Two approaches are currently being used for describing the effects of water in soil: the mechanistic and energy approaches.[13] The mechanistic approach is based on measurements of negative pore water pressure in specimens using special consolidometers and pressure membrane devices. For these measurements,[9] membranes with small pore sizes are used to prevent cavitation of water in the membrane. Air pressures may therefore be applied to the soil specimen to increase the positive or decrease the negative pore water pressure without loss of air or loss of control of the volume of water entering or leaving the specimen. Water will be forced from the soil if air pressures are sufficient to cause positive pore water pressures. Water will be imbibed into the soil if the pore water pressures are negative. Applied air pressures that lead to no flow of water into or out of the specimen are denoted as the negative pore water pressures or soil suctions.

23. Evaluation of soil suction by the mechanistic approach is encumbered with conceptual and measurement problems. Olson and Langfelder[11] observed that the force fields of the clay minerals, which are responsible for the microscale mechanisms that cause swell, very likely cause the actual pore water pressure to be positive near the surfaces of the clay mineral particles. The mechanistic approach evaluates an equivalent negative pore water pressure or soil suction that is needed to pull the pore water out of the soil. The equivalent pore pressure measurement is performed with a water content that changes during the measurement because water is forced into or out of the specimen. The equivalent pore pressure also neglects much of the contribution to soil suction from the concentration of ions in the pore fluid if the ions are able to pass through the membrane of the apparatus. The ions will pass through membranes made of porous stones or ceramic plates.[9] Hysteresis is also observed in the soil

suction-water content relationships determined for a single specimen with the pressure membrane device.

24. Determinations of soil suction using the mechanistic approach must be corrected with various calibration factors. A correction is needed to adjust void ratio computations for deformations of the apparatus. Another correction is needed to adjust water content computations for the accumulation of air beneath the porous plate that results by diffusion of air from the applied air pressure through the soil specimen.[9] Minute voids or fissures in the seal between the porous plate and ring surrounding the plate contribute to the loss of volume control of the air. The volume of air adds to the volume of water that is forced from the specimen. In general, test procedures using the mechanistic approach are often tedious and time consuming and data reduction is laborious.

25. Evaluation of soil suction by the energy approach is a more general method based on the principle of thermodynamics. Soil suctions evaluated by both the mechanistic and energy approaches can lead to similar magnitudes on similar specimens,[9,10,14] but the two concepts are different. The method adopted herein for characterizing swell behavior by soil suction is based on the energy approach where soil suction is evaluated from measurements of relative humidity in soils determined with thermocouple psychrometers.

Energy concept

26. The most fundamental expression of the state of water in soil is the relative free energy of the soil water. The force that causes available water to move into soil is expressed quantitatively in terms of the free energy of the soil water relative to the available water outside of the soil. The free energy (Δf) needed to move free pure water into the pores of soil containing the soil water is[12]

$$\Delta f = RT \log_e \frac{p}{p_o} \qquad (1)$$

where

R = ideal gas constant, 82.06 cc-atm/K*

T = absolute temperature, K

p = vapor pressure of the pore water in the soil, atm

p_o = vapor pressure of free pure water, atm

p/p_o = relative humidity

The change in free energy due to movement of the free pure water into the pore water is usually given in terms of an equivalent total soil suction

$$\tau^o = \frac{1.058RT}{v} \log_e \frac{p}{p_o} \tag{2}$$

where

τ^o = total soil suction, tsf

v = volume of a mole of liquid water, 18.02 cc/mole

The superscript "o" after τ means the soil is not subject to any confining pressure, except for atmospheric pressure.

27. Total soil suction has been defined for convenience as the sum of osmotic τ_s^o and matrix τ_m^o components, Table 2.[12]

$$\tau^o = \tau_s^o + \tau_m^o \tag{3}$$

The osmotic suction by the definition in Table 2 is due entirely to the concentration of soluble salts in the pore water and it is consequently related mostly to the osmotic repulsion mechanism. The osmotic suction is expressed by

$$\tau_s^o = \frac{1.058RT}{v} \log_e \frac{p_s}{p_o} \tag{4}$$

where p_s is the vapor pressure of the free pore water solution, atm. The osmotic suction can increase as water evaporates from the soil

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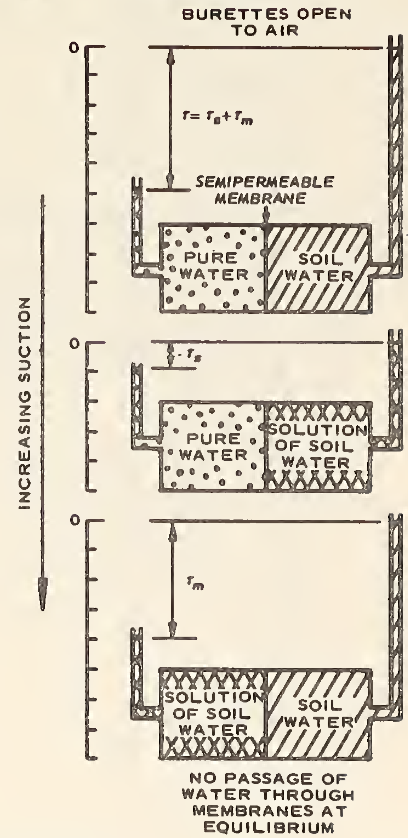
* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page v.

Table 2

Definitions of Suction

Term	Symbol	Definition*	Illustration
Total suction	τ	The negative gage pressure, relative to the external gas pressure** on the soil water, to which a pool of pure water must be subjected in order to be in equilibrium through a semipermeable (permeable to water molecules only) membrane with the soil water	
Osmotic (solute) suction	τ_s	The negative gage pressure to which a pool of pure water must be subjected in order to be in equilibrium through a semipermeable membrane with a pool containing a solution identical in composition with the soil water	
Matrix (soil water) suction	τ_m	The negative gage pressure, relative to the external gas pressure** on the soil water, to which a solution identical in composition with the soil water must be subjected in order to be in equilibrium through a porous permeable wall with the soil water	



* From Reference 12 of text.

** The magnitude of the matrix suction is reduced by the magnitude of the external gas pressure. The osmotic suction is determined by the concentration of soluble salts in the pore water and can be given by $\tau_s = \frac{RT}{v_w} \log_e \frac{P}{P_o}$ where R is the universal gas constant, T is absolute temperature, v_w is volume of a mole of liquid water, P is vapor pressure of the pore-water extract, and P_o is vapor pressure of free pure water.

because the concentration of ions in the remaining soil water can increase. The osmotic suction does not change with confining pressure.

28. The matrix suction in swelling soils is related mostly to forces arising from clay particle attraction and cation hydration in addition to surface tension effects. The matrix suction is expressed by

$$\tau_m^o = \frac{1.058RT}{v} \log_e \frac{p}{p_o} \tag{5}$$

and can be evaluated directly from the relative humidity of the soil when the chemical composition of the pore water contributes negligible osmotic suction. The matrix suction will decrease with increasing confining pressure.

Evaluation using
thermocouple psychrometers

29. The thermocouple psychrometer measures the relative humidity in the soil by a technique called Peltier cooling.[15] By causing a small direct current of about 4 to 8 milliamperes to flow through the thermocouple junction (see Figure 2) for about 15 seconds in the correct direction, this junction will cool and water will condense on it when the dewpoint temperature is reached. Condensation of this water inhibits further cooling of the junction and the voltage developed between the thermocouple and reference junction is measured by a microvoltmeter. Figure 3 shows the equipment used at WES to measure the output voltage.

30. The voltage outputs of the psychrometers are calibrated by tests with salt solutions such as potassium chloride that produce a given relative humidity for known concentrations (Table 3).[16] The relative humidities are converted to osmotic soil suctions by Equation 4, which are also total soil suctions of these solutions. The resultant calibration curve of the commercial psychrometers when using the equipment in Figure 3 is linear:

$$\tau^o = 2.82E_{25} - 4.4 \tag{6}$$

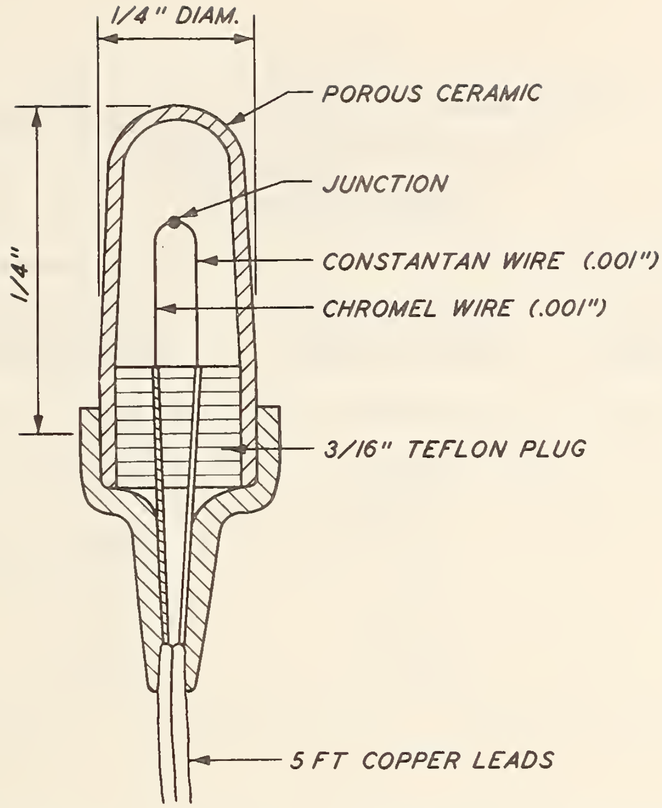


Figure 2. Diagram of thermocouple psychrometer

Figure 3. Readout equipment for thermocouple psychrometers

Table 3

Concentration of Potassium Chloride for Certain Relative Humidities (from Reference 16)

Gram-Formula Weight/ 1000 g Water, Molal	Grams of KCl/ 1000 ml Water	Relative Humidity, %	Suction at 25°C, tsf
0.05	3.728	99.83	2.4
0.20	14.91	99.36	9.3
0.50	37.27	98.42	22.8
1.00	74.55	96.84	46.0
2.00	149.10	93.68	93.6

where

τ^{o} = total soil suction, tsf

E_{25} = microvolt output at 25°C

Typical voltages vary from less than 1 microvolt for relative humidities close to 100 percent or total soil suctions less than 1 tsf to about 25 microvolts for humidities of about 95 percent or total soil suctions of about 60 tsf. The reliable lower limit of these soil suction evaluations is about 1 tsf. Equipment was developed elsewhere using a special constant temperature bath and psychrometers with more than one junction that can be used for measurement of suctions less than 1 tsf with reliability of about 10 percent.[14]

FIELD SAMPLING AND LABORATORY TESTING

31. The research program for the verification of the natural microscale mechanisms involved three major goals: (a) organize and perform a systematic field sampling and laboratory testing program to evaluate the physical and physicochemical properties of selected expansive soils within the continental United States; (b) develop and initiate a field monitoring program for highway sections on expansive soil subgrades in selected states to provide field situation data on seasonal and total deformations, variations in subgrade moisture conditions, and pavement performance (i.e., roughness, in situ strength, serviceability rating) for correlation with subsequent laboratory results; and (c) establish interrelationships between the microscale mechanisms and physical and physicochemical properties from which deductions could be made on the role of the mechanisms in the volume change phenomenon. The primary purpose of goal b was to provide data for subsequent tasks involving evaluation of treatment alternatives for expansive soils and will be covered in much greater detail in subsequent reports. The field monitoring data are of secondary importance with regard to this portion of the program. The remaining major goals provide the major thrust of the research task on mechanism.

Field Sampling Program

32. The field sampling program was initiated through contacts with 11 State Highway Agencies in which agency representatives were requested to recommend appropriate geologic formations and site locations based on the simple criterion that the material be representative of an areally extensive deposit of expansive soil which poses problems as defined by the State Highway Agency. It was also requested that the sites be located along the alignment of a recently constructed highway or in the graded alignment of a proposed highway. As a result of the State Highway Agency recommendations, 20 field sampling sites were selected (see Figure 4). Table 4 summarizes the approximate locations

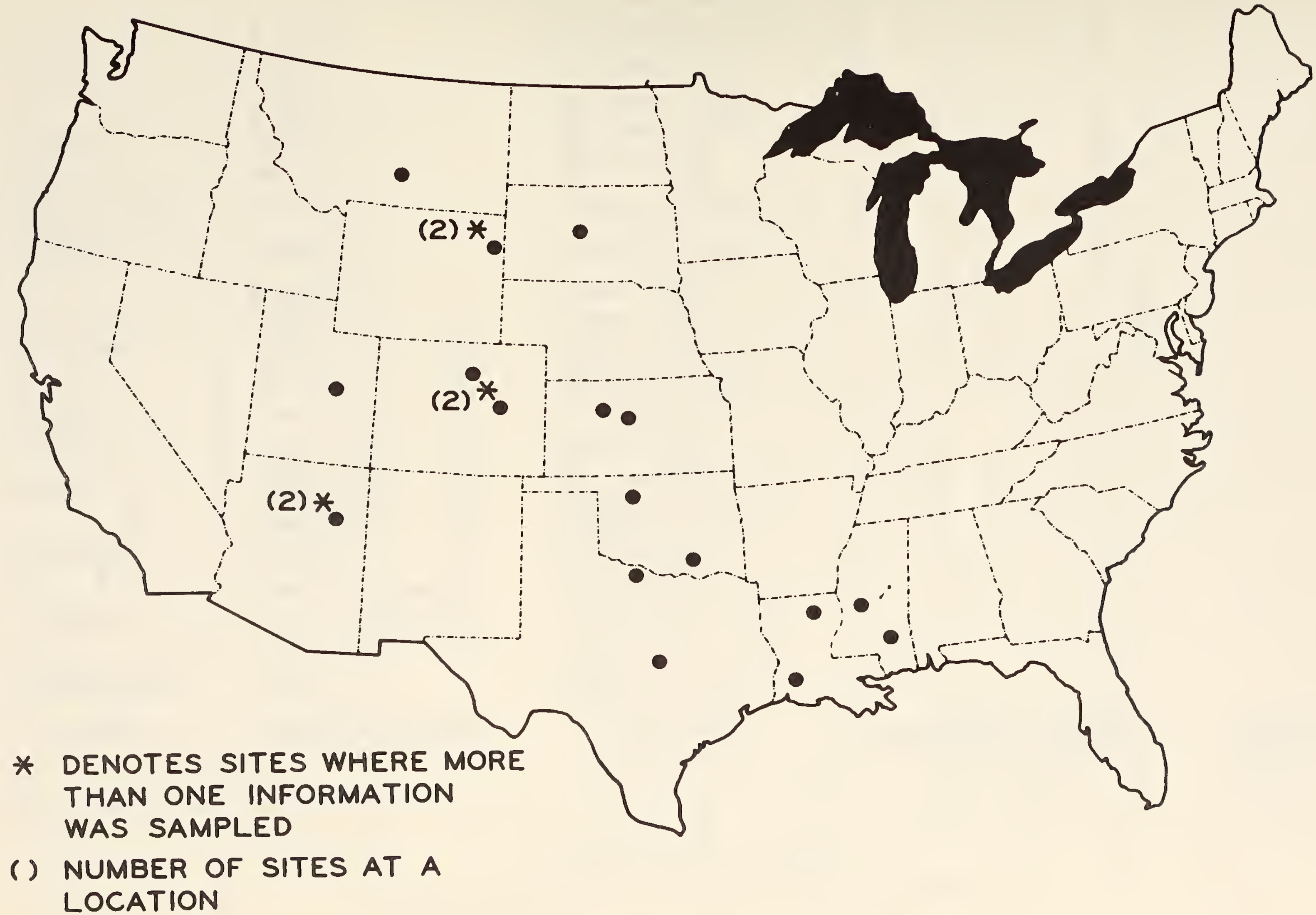


Figure 4. Location of field sampling sites

Table 4

Geologic Formations and Approximate Locations for Field Sampling Sites

State	Geologic Formation	Approximate Location	Type of Sample: Undisturbed	Type of Sample: Disturbed	Field Monitoring Section
Mississippi	Yazoo	Jackson, Miss.	X	X	X
	Hattiesburg	Hattiesburg, Miss.	X	X	
Louisiana	Alluvial Clay	Monroe, La.	X	X	
	Prairie Terrace	Lake Charles, La.	X	X	
Oklahoma	Washita	Durant, Okla.	X	X	
	Hennessey	Hennessey, Okla.	X	X	
Texas	Taylor Marl	San Antonio, Tex.	X	X	X
	Vale	Vernon, Tex.	X	X	
Kansas	Blue Hill	Hays, Kans.	X	X	
	Graneros	Ellsworth, Kans.	X	X	
Colorado	Pierre	Limon, Colo.	X	X	X
	Laramie	Limon, Colo.	X	X	
	Denver	Denver, Colo.	X	X	X
Montana	Bearpaw	Billings, Mont.	X	X	X
South Dakota	Pierre	Pierre, S. Dak.	X	X	X
Utah	Mancos	Price, Utah	X	X	
Wyoming	Pierre	Newcastle, Wyo.	X	X	
	Mowry	Newcastle, Wyo.	X	X	
Arizona	Chinle	Holbrook, Ariz. (2 sites)	X	X	X

and geologic formations of the field sampling sites. More detailed site location information, site description, site geology, sample description, description of climate, and summary of climatic data are given in the respective discussion sections for the individual sites in the appendix to this report.

33. At each sampling site the materials were sampled to a depth of approximately 15 ft. A minimum of ten 5.0-in.-ID Shelby-tube samples were taken from two boreholes at each site. When harder materials were encountered, a specially modified Denison-type double-tube sampler developed at WES was used.[17] Half of the Shelby-tube samples were extruded, cut in half (usually a 2-ft-long specimen), and sealed in wax inside a cardboard container. The remaining Shelby-tube samples were stored in the sampling tubes with expanding packers to prevent moisture loss. In addition to the undisturbed samples, approximately 500 lb of disturbed material was taken from shallow pits with the sample taken between the 1- and 3-ft depths. Samples were trucked to Vicksburg and stored in a cool dry warehouse. Selected cardboard container samples were stored in a 100 percent humidity moist room to observe the influence of storage techniques; disturbed materials were stored in self-sealing 55-gal Teflon-lined drums.

Laboratory Testing Program

34. Since no specific tests are available to independently measure the contributions of the microscale mechanisms, a phenomenological approach was taken to accomplish the task. The laboratory testing program was designed to determine pertinent physical, physicochemical, and mineralogic properties so that the role of the microscale mechanisms in causing volume change could be inferred from the measured parameters' influence on the magnitude and rate of volume change. In other words, several of the measured parameters are known to be related to the microscale mechanisms and the influence of the mechanisms on volume change was inferred via the influence of the measured

parameters. The laboratory testing program is summarized in Table 5. The following paragraphs briefy describe the testing procedures for which some variation from the standard method was used or no standard method exists.

Natural water content and density

35. No special procedure was used for determining these values. The natural water contents and densities were established from the initial condition for the overburden swell test.

Classification

36. Visual classifications and descriptions of the specimens were obtained prior to testing. Unified Soil Classification System (USCS) descriptions were made in accordance with EM 1110-2-1906.[18] AASHTO classifications were made in accordance with Recommended Practice AASHTO Designation M-145-73.[19,20]

Specific gravity

37. No special procedure was used for this test; however, since several of the samples involved shales, special specimen preparation procedures were used[18] for this test, grain-size distribution, and Atterberg limits.

Grain-size distribution

38. Grain-size distribution was determined using combined sieve and hydrometer analysis.

Shrinkage properties

39. Bar linear shrinkage values were determined in accordance with procedures specified by the Texas Department of Highways and Public Transportation,[21] Test Method Tex-107-E (Revised January 1, 1972).

40. Shrinkage limit values were determined using a modified procedure which does not require the use of mercury. The procedure involves mixing the specimen to a moisture content (estimated) near the liquid limit. Using a glass plate and clear plastic or brass ring (ID = 1.75 in., height = 0.5 in., volume = 20.25 cc), place the soil in the ring and strike the top surface even with the ring. Weigh the soil and ring and allow to air-dry until a color change from dark to

Table 5

Summary of Laboratory Testing Program

Natural Water Content and Density
Classification (Visual, Unified, AASHTO)
Specific Gravity
Grain-Size Distribution
Atterberg Limits

Shrinkage Properties
  Bar Linear Shrinkage
  Remolded Shrinkage Limit
  Free Swell by Graduated Cylinder

Compaction
Overburden Swell Test
Constant Volume Swell Pressure Test
Total Soil Suction
Soil pH
Cation Exchange Capacity
Exchangeable Cations (K, Na, Ca, Mg)
Pore Fluid Cations (K, Na, Ca, Mg)
Mineralogy Determination (X-Ray Diffraction)
Soil Fabric (Scanning Electron Microscope)

light occurs, then oven-dry. Weigh and determine the average thickness and diameter of the soil pat to compute the volume. Computations from this point are similar to the AASHTO Procedure, T-92-68.[20]

41. Free swell by graduated cylinder is not actually a shrinkage property, but was included here because it does reflect volume change. In this test, 10.0 g of oven-dried soil is placed in a 100-ml graduated cylinder, the surface leveled, and volume recorded; then the cylinder is filled with distilled water. The increase in volume of the soil after 48 hr is divided by the initial volume to obtain the free swell parameter.

Compaction

42. Compaction properties were determined using AASHTO Designation T-99, Method A.[20]

Overburden swell test

43. The volume change (swell) of undisturbed samples was measured using an odometer-type test utilizing the loading sequence shown in Figure 5. A seating load is applied for a specified time period followed by the overburden pressure. The sample is then inundated, allowed to swell to equilibrium, consolidated back to e_o, and rebounded.

Constant-volume swell pressure test

44. The stress component of expansive materials (swell pressure) was measured using an odometer-type test utilizing the loading sequence shown in Figure 6. The procedure is identical with the overburden swell test up to inundation of the sample. Following inundation, load is applied to the sample to maintain constant void ratio. When the swell pressure is fully developed, the specimen is rebounded, consolidated back to e_o, and rebounded.

Total soil suction

45. Total soil suction was evaluated using the thermocouple psychrometer technique and equipment previously described. The test procedure begins by cutting an undisturbed soil sample into small 1-in. (approximate dimension) cubes totaling approximately 100 to 200 g for each specimen. A total of 12 individual specimens were used for each sample. Each specimen was placed in a pint-capacity metal can. Small

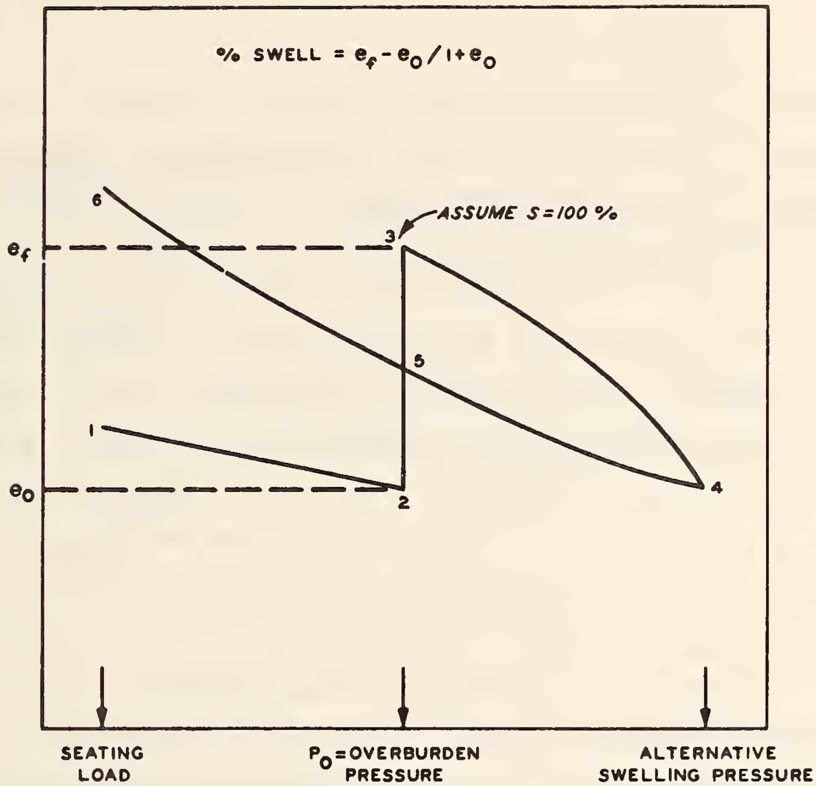


Figure 5. Loading sequence for overburden swell test

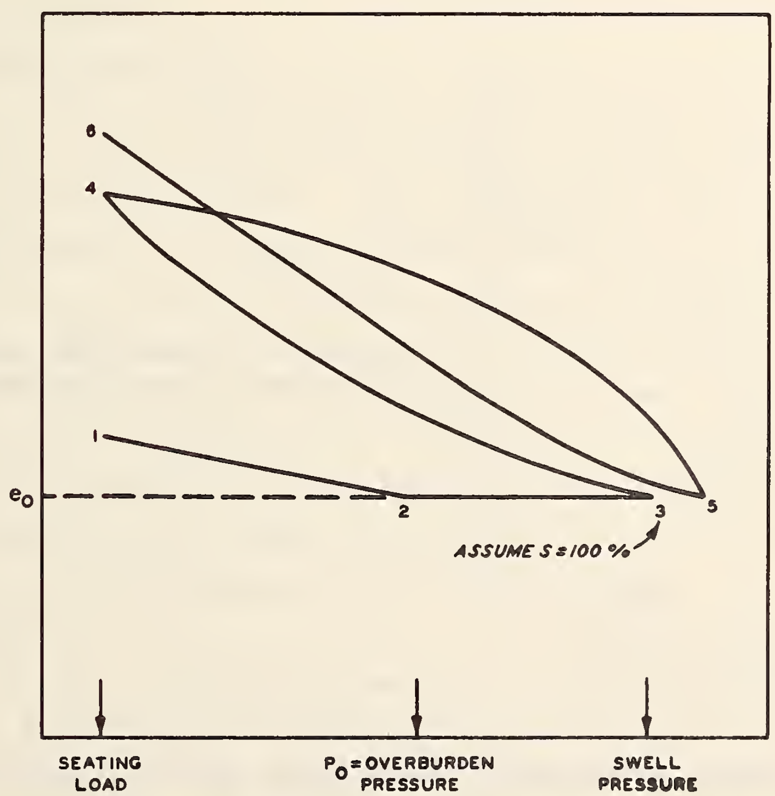


Figure 6. Loading sequence for constant-volume swell pressure test

amounts of distilled water were added to four of the cans, and six were left open for various time periods up to 48 hr to increase or decrease, respectively, the water contents. A No. 13-1/2 rubber stopper with a thermocouple psychrometer inserted through the stopper was used to seal the cans. The entire assembly was placed in a foamed polystyrene chest (capacity, 6 metal containers) to reduce temperature fluctuation problems. Cables from the psychrometers were passed through the lid of the chest and connected to the readout equipment. Temperature equilibrium in the chest was usually achieved within 3 to 4 hr following closure of the chest. Equilibrium of the relative humidity in the air in the chest and the relative humidity in the soil specimen was usually obtained in 48 hr. The data points of the 12 specimens of the same soil at various water contents and soil suctions were plotted to establish a single soil suction (log scale) versus water content relationship, Figure 7. Further details concerning evaluation of soil suction by this procedure are presented in Reference 22.

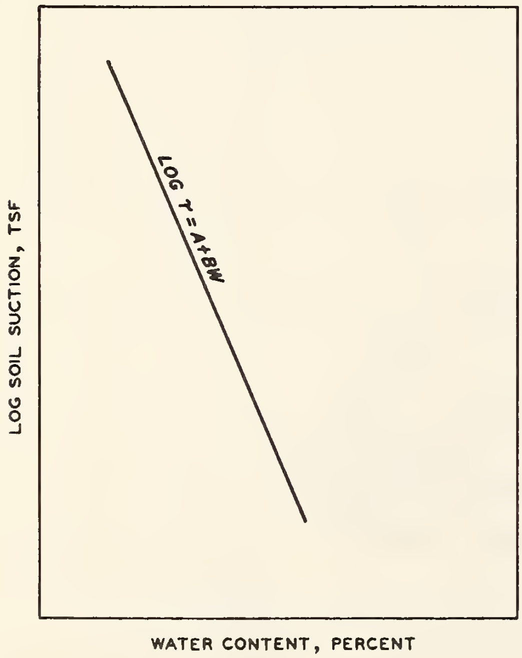


Figure 7. Typical soil suction versus water content relationship

<u>Soil pH</u>

46. Soil pH values were determined on soil slurries (1:1 soil-water ratio) using an electronic pH meter.

Cation exchange capacity (CEC)

47. CEC values were determined using procedures specified for ammonium acetate saturation,[23] Ion-Exchange Analysis Method 5A1.

Exchangeable cations

48. The amounts of exchangeable cations (sodium, calcium, magnesium, potassium) were determined using Atomic Absorption (Flame Photometry) techniques. The values were measured in the leachate from the CEC determination.

Pore fluid cations

49. The amounts of pore fluid cations (sodium, calcium, magnesium, potassium) were determined using Atomic Absorption (Flame Photometry) techniques. The values were measured in the leachate from a "saturated soil paste."[23] (Distilled water added to soil until the soil paste glistens as it reflects light, flows slightly when container is tipped, and slides freely and cleanly off a spatula except for high clay content soils.)

Mineralogy determination

50. The clay mineralogy and accessory mineral composition were determined for all samples using generally accepted standard X-ray diffraction (XRD) techniques. These techniques consisted of examination of diffractograms of randomly oriented, powdered specimens of the bulk sample for the purpose of identifying the gross composition (nonclay minerals, cements, etc.) and analysis of diffractograms of the oriented, sedimented minus 2-micrometre fraction of the sample. This latter analysis permitted detailed identification of the clay mineral suite and included solvation as well as other techniques for distinguishing between various clay minerals. Approximate quantitative mineralogic compositions were estimated from the diffractograms.

Soil fabric

51. The soil fabric of samples from each of the field sampling sites was studied using a Scanning Electron Microscope (SEM). The SEM study specimens were taken from sections of the undisturbed sample adjacent to the odometer swell and swell pressure test specimens. Two cubic specimens (dimension approximately 2 in.) were cut from the

undisturbed sample and were then freeze-dried in dry ice for approximately 2 hr. After freeze-drying, the cubic specimens were fractured exposing the surface to be viewed in the SEM. The fractured surfaces were coated with approximately 50 Å of carbon and 150 Å of gold palladium to preserve the surfaces. The two cubic specimens were cut so that the final fractured surfaces would represent views normal to the x- and y-axes, Figure 8. One view looks down the vertical or y-axis onto a specimen surface normal to this axis and represents a bedding plane surface. The second view is normal to the horizontal or x-axis, and the specimen surface is normal to the bedding planes or stratifications.

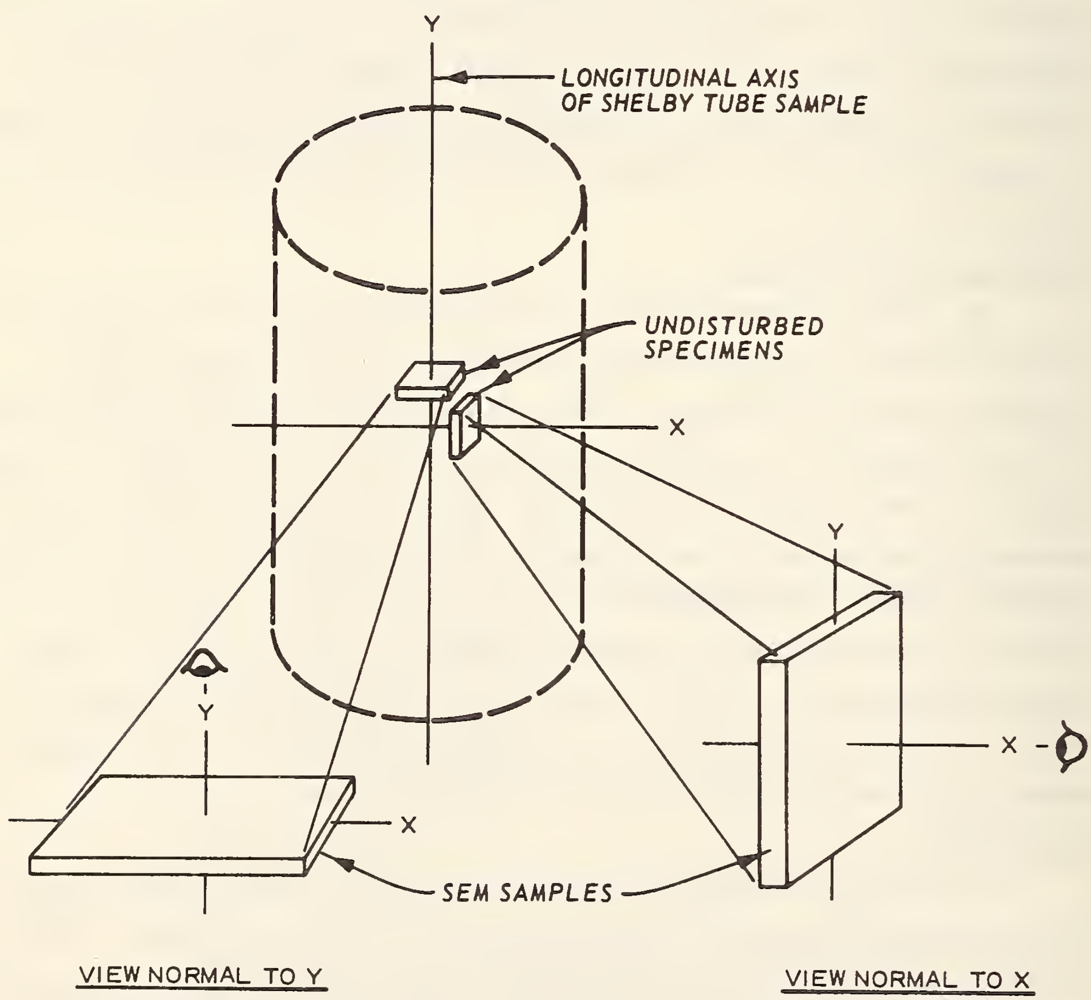


Figure 8. Orientation of SEM specimens relative to axis of undisturbed sample

Results of Laboratory Tests

52. The laboratory testing program as described in the previous discussions encompassed a majority of the currently accepted and used parameters which reflect pertinent properties from both the soil mechanics and soil science fields. All of the tests except compaction were conducted on undisturbed specimens taken during the sampling program. To simplify the succeeding section of this report, the measured parameters are grouped and presented in Tables 6 through 13. The following discussions provide a brief description of the information included in each of the tables.

Table 6: Site Information and Soil Classification

53. The information in Table 6 includes the sampling site number which has been assigned to each of the sampling sites and will be used throughout the remainder of the report when referring to a specific site. A general site location, geologic formation, boring and sample number, and sample depth are included for the identification of the specimens tested. In the appendix to this report, a site location map, detailed site location information, and site description are included to provide a better understanding of the site locale. Also included in the appendix are descriptions of the site geology and descriptions of the disturbed samples. These sample descriptions were prepared using binocular microscopic examination as well as visual review. Colors and their numerical designations were based upon Reference 24. Argillaceous rock classification was that of Folk.[25] The remainder of Table 6 summarizes the classification of the materials, natural moisture content and density, and the compaction properties. Compaction curves are included in the appendix for each of the sampling sites.

Table 7: Basic Physical Properties

54. The information in Table 7 includes the specific gravity, percent minus U. S. No. 200 sieve, percent minus 2 micrometres (percent clay), and the Atterberg limits and associated indices pertinent to the materials involved. Grain-size distribution curves for the sampling sites are included in the appendix.

Table 6

Summary of General Site Information and Soil Classifications

Site No.	Site Location	Geologic Formation	Boring/ Sample No. Depth, ft	Natural Moisture Content %	Natural Dry Density pcf	Optimum* Moisture Content %	Maximum* Dry Density pcf	Soil Classification USCS**	Soil Classification AASHTO†
1	Jackson, Miss.	Yazoo	U-2/1/1.0-3.2	43.6	77.5	26.8	78.7	CH	A-7-5 (81)
2	Hattiesburg, Miss.	Hattiesburg	U-2/1/1.0-2.9	26.6	95.2	21.3	101.0	CH	A-7-6 (36)
3	Monroe, La.	Alluvial Material	U-1/1/1.0-2.8	46.0	71.3	30.8	84.5	CH	A-7-5 (68)
4	Lake Charles, La.	Prairie Terrace Material	U-2/1/1.0-3.1	27.3	96.5	15.6	110.8	CH	A-7-6 (33)
5	San Antonio, Tex.	Taylor	U-2/4/3.5-5.1	24.0	95.4	19.6	101.2	CH	A-7-5 (35)
6	Vernon, Tex.	Vale	U-1/4/4.8-7.2	13.8	119.7	17.4	108.9	CL	A-6 (11)
7	Durant, Okla.	Washita	U-2/2/3.5-4.7	15.4	117.9	18.9	105.5	CL	A-7-6 (30)
8	Hennessey, Okla.	Hennessey	U-1/2/3.5-5.6	12.5	124.9	19.4	109.5	CL	A-7-6 (25)
9	Holbrook, Ariz., No. 1, I-40	Chinle	U-2/1/2.5-4.2	9.4	111.5	21.3	97.9	CL	A-6 (10)
10	Holbrook, Ariz., No. 2, SH 180	Chinle	U-2/1/2.0-4.3	16.5	103.6	21.3	97.9	CH	A-7-6 (24)
11	Price, Utah	Mancos	U-1/1/1.2-3.2	6.6	121.2	19.4	106.2	CL	A-7-6 (27)
12	Hays, Kans.	Blue Hill	U-2/1/1.4-3.4	26.2	98.4	26.4	94.7	CH	A-7-6 (58)
13	Ellsworth, Kans.	Graneros	U-2/1/2.0-4.3	16.7	112.8	28.6	85.8	CL	A-7-6 (22)
14	Limon, Colo., No. 1, I-70	Pierre	U-1/5/4.2-6.3	26.4	98.2	22.2	97.7	CH	A-7-6 (35)
15	Limon, Colo., No. 2, I-70	Laramie	U-1/1/3.4-5.0	38.2	78.8	31.8	83.4	CH	A-7-6 (44)
16	Denver, Colo.	Denver	U-3/4/5.7-7.8	14.8	101.1	25.1	95.9	CL	A-6 (10)
17	Newcastle, Wyo., No. 1, SH 16	Mowry	U-2/1/3.0-5.2	26.4	97.5	25.2	96.1	CH	A-7-6 (31)
18	Newcastle, Wyo., No. 2, US 85	Pierre	U-2/1/1.6-3.8	15.8	107.7	22.2	98.5	CH	A-7-6 (25)
19	Billings, Mont.	Bearpaw	U-2/1/3.1-4.6	17.6	110.8	21.1	102.3	CH	A-7-6 (50)
20	Reliance, S. Dak.	Pierre	U-2/1/1.7-3.9	31.4	83.6	38.5	78.5	CH	A-7-5 (42)

* AASHTO T-99, Method A.
** Unified Soil Classification System.
† American Association of State Highway and Transportation Officials.

Table 7

Summary of Specific Gravity, Grain-Size Distribution, and Atterberg Limits and Indices

Site No.	Specific Gravity	Grain Size, % No. 200	Grain Size, % 2 μm	Liquid Limit %	Plastic Limit %	Plasticity Index	Activity	Liquidity Index
1	2.69	98	82	104	36	68	0.83	0.11
2	2.68	84	38	61	20	41	1.08	0.16
3	2.72	96	57	96	38	58	1.02	0.14
4	2.72	82	37	56	17	39	1.05	0.26
5	2.73	97	36	58	27	31	0.86	-0.10
6	2.83	89	38	34	21	13	0.34	-0.55
7	2.75	98	43	48	21	27	0.63	-0.21
8	2.82	98	57	47	23	24	0.42	-0.44
9	2.75	69	23	34	18	16	0.70	-0.54
10	2.81	84	13	54	29	25	1.92	-0.50
11	2.74	97	42	46	20	26	0.62	-0.52
12	2.75	98	61	75	24	51	0.84	0.04
13	2.63	91	32	49	28	21	0.66	-0.54
14	2.80	98	44	56	25	31	0.70	0.05
15	2.76	98	64	63	24	39	0.61	0.36
16	2.72	63	33	38	19	19	0.58	-0.22
17	2.71	91	24	55	25	30	1.25	0.05
18	2.78	97	45	50	28	22	0.49	-0.55
19	2.76	97	44	69	24	45	1.02	-0.14
20	2.72	94	61	80	34	46	0.75	-0.06

Table 8: Shrinkage Properties

55. The information in Table 8 includes the shrinkage limit and ratio as determined by the modified testing procedure; the shrinkage index, which is the liquid limit minus the shrinkage limit; and the Bar Linear Shrinkage (BLS), which is a standard test used by the Texas Department of Highways and Public Transportation. Free swell measured in a graduated cylinder, although not a shrinkage test, is included since it supposedly reflects a measured volume change parameter.

Table 9: Overburden Swell Test Data

56. The information in Table 9 summarizes the initial (overburden), end of swell (degree of saturation assumed equal to 100 percent), and end of test conditions of the specimens. The measured deformation (Δe) and corresponding percent swell are also tabulated. Void ratio versus log pressure curves for each of the specimens are included in the respective sampling site sections of the appendix. The overburden pressure was supposed to reflect the in situ conditions of wet density and depth to the test specimen; however, because of an error in testing assignments, the overburden pressure was arbitrarily set at 0.28 tsf for all sampling sites. Following completion of the overburden swell testing, the actual overburden pressures were evaluated, and in cases where the actual and tested overburden pressures did not agree, a second specimen was tested. The results of these tests will be reported in a subsequent report. One specimen from sampling site 11 (Price, Utah) did not expand under the applied overburden pressure. The measured swell for this specimen corresponds to a pressure of 0.015 tsf (seating load).

Table 10: Constant-Volume Swell Pressure Test Data

57. The information in Table 10 includes a summary of initial (overburden) and end of test conditions of the specimens as well as the measured swell pressure. Void ratio versus log pressure curves for each of the specimens are included in the respective sampling site sections of the appendix. The same comment on actual versus tested

Table 8

Summary of Measured Shrinkage Properties

Site No.	Shrinkage Limit %	Shrinkage Ratio	Shrinkage* Index	Bar Linear Shrinkage %	Free** Swell %
1	9.8	1.83	94.2	23.2	90
2	14.5	1.86	46.5	19.2	50
3	20.5	1.70	75.5	19.5	57
4	12.4	1.93	43.6	17.7	37
5	16.2	1.73	41.8	18.8	32
6	14.8	1.89	19.2	20.0	25
7	20.3	1.61	27.7	12.1	26
8	18.9	1.76	28.1	14.4	13
9	14.5	1.85	19.5	13.4	43
10	16.8	1.77	37.2	12.8	47
11	19.8	1.72	26.2	26.2	23
12	17.6	1.75	57.4	20.2	52
13	23.6	1.58	25.4	13.6	40
14	20.2	1.68	35.8	14.4	36
15	18.3	1.72	44.7	15.6	56
16	15.5	1.83	22.5	11.0	32
17	19.1	1.75	35.9	12.0	24
18	19.0	1.72	31.0	12.6	43
19	12.8	1.92	56.2	19.6	21
20	27.3	1.49	52.7	16.0	38

* Shrinkage index = liquid limit - shrinkage limit.
** Percent free swell measured in graduated cylinder.

Table 9

Summary of Data from Overburden Swell Tests

Site No.	Initial Conditions*				End of Swell Conditions				End of Test Conditions				Δe**	Swell† %
	e_o	w_o	S_o	γ_o	e_f	w_f	S_f	γ_f	e	w	S	γ		
1	1.165	43.6	100.7	77.5	1.331	49.5	100	72.0	1.502	55.5	99.4	67.1	0.166	7.67
2	0.757	26.6	94.2	95.2	0.774	28.9		94.3	0.799	30.0	100+	93.0	0.017	0.97
3	1.379	46.0	90.7	71.3	1.382	50.8		71.2	1.394	48.3	94.2	70.9	0.003	0.13
4	0.7593	27.3	97.8	96.5	0.7607	28.0		96.4	0.769	28.1	99.5	96.0	0.0014	0.08
5	0.7851	24.0	83.5	95.4	0.7966	29.2		94.8	0.823	31.6	100+	93.5	0.0115	0.64
6	0.4750	13.8	82.2	119.7	0.4753	16.8		119.7	0.485	22.7	100+	118.9	0.0003	0.02
7	0.4546	15.4	93.2	117.9	0.4608	16.8		117.5	0.472	16.6	96.7	116.6	0.0062	0.43
8	0.4082	12.5	86.4	124.9	0.4084	14.5		124.9	0.409	13.3	91.6	124.9	0.0002	0.01
9	0.5387	9.4	48.0	111.5	0.5588	20.3		110.1	0.590	19.0	88.7	108.0	0.0201	1.31
10	0.6921	16.5	67.0	103.6	0.7338	26.1		101.1	0.787	26.8	95.6	98.2	0.0417	2.46
11††	0.4106	6.6	44.0	121.2	0.4220	15.4		120.2	0.417	10.2	66.4	119.0	0.0114	0.81
12	0.7446	26.2	96.8	98.4	0.7655	27.8		97.2	0.803	29.1	99.6	95.2	0.0209	1.20
13	0.4554	16.7	96.4	112.8	0.4605	17.5		112.4	0.463	16.6	94.5	112.2	0.0051	0.35
14	0.7791	26.4	94.9	98.2	0.7944	28.4		97.4	0.826	28.7	97.1	95.7	0.0153	0.86
15	1.185	38.2	89.0	78.8	1.188	43.0		78.7	1.203	41.8	95.9	78.2	0.003	0.14
16	0.6787	14.8	59.3	102.1	0.7097	26.1		99.3	0.732	25.4	94.3	102.0	0.031	1.85
17	0.734	26.4	97.5	97.5	0.748	27.6		96.7	0.776	28.3	98.6	95.2	0.014	0.81
18	0.6105	15.8	71.9	107.7	0.6706	24.1		103.8	0.721	23.6	91.2	107.0	0.0601	3.73
19	0.5542	17.6	87.7	110.8	0.5598	20.3		110.4	0.569	22.4	92.2	110.3	0.0056	0.36
20	1.030	31.4	82.9	83.6	1.118	41.1	100	80.1	1.199	42.3	95.9	77.3	0.088	4.33

Note: e = void ratio, w = moisture content (%), S = degree of saturation (%), γ = dry density (pcf).
* Corresponds to overburden conditions on e-log p plot.
** $\Delta e = e_f - e_o$.
† % swell = $\Delta e/1 + e_o$.
†† No swell developed under applied overburden pressure, indicated swell is for applied seating load surcharge.

Table 10

Summary of Data from Constant-Volume

Swell Pressure Tests

Site No.	Initial Conditions*				End of Test Conditions				Swell Pressure tsf
	e_o	w_o	S_o	γ_o	e	w	S	γ	
1	1.155	43.6	100+	77.9	1.477	55.0	100+	67.8	3.82
2	0.716	26.1	97.7	97.5	0.765	29.2	100+	94.8	0.96
3	1.265	45.1	97.0	79.4	1.282	46.1	97.8	74.4	0.43
4	0.686	24.4	96.8	100.7	0.697	25.1	98.1	100.1	0.35
5	0.840	27.3	88.8	92.6	0.884	28.5	88.0	90.4	0.90
6	0.421	13.6	91.5	124.3	0.425	14.1	94.1	124.0	0.66
7	0.544	18.0	91.0	111.1	0.559	19.2	94.5	110.1	0.65
8**	0.603	16.0	74.9	109.8	0.603	20.2	94.3	109.8	0.06
9	0.548	9.2	46.2	110.9	0.594	18.9	87.6	107.7	1.17
10	0.727	17.4	67.3	101.5	0.771	27.1	98.9	99.0	0.93
11**	0.306	8.6	77.0	130.9	0.310	10.5	92.0	129.4	0.17
12	0.736	25.8	96.4	98.9	0.784	28.0	98.2	96.2	0.95
13	0.432	14.1	85.9	114.6	0.439	14.9	86.2	114.1	1.16
14	0.765	24.1	88.2	110.1	0.816	27.0	92.5	96.3	0.80
15	1.125	36.3	89.1	81.0	1.145	39.9	96.2	80.3	0.38
16	0.750	13.3	48.2	97.0	0.768	25.5	90.5	96.8	1.00
17	0.725	25.4	94.9	98.0	0.793	28.4	96.9	94.3	1.07
18	0.677	15.8	64.8	103.4	0.751	21.8	80.6	99.2	2.37
19	0.589	17.7	83.0	108.4	0.586	20.8	95.1	108.0	0.59
20	0.990	32.3	88.7	85.3	1.132	41.5	99.6	79.6	2.54

Note: e = void ratio, w = moisture content (%), S = degree of saturation (%), γ = dry density (pcf).

* Corresponds to overburden conditions on e-log p plot.

** No swell pressure developed under applied overburden, indicated pressure is for applied seating load surcharge.

overburden pressure applies to the constant-volume swell pressure test. Two specimens, sampling sites 8 (Hennessey, Oklahoma) and 11 (Price, Utah), did not develop a swell pressure under the applied overburden pressure. The swell pressure shown was measured under the seating load (0.015 tsf).

Table 11: Soil Moisture Suction Data

58. The information in Table 11 includes the natural moisture content and the corresponding total soil suction of the test specimens. The A and B parameters are the y-intercept and slope, respectively, of the soil suction (log) versus moisture content relationship which has the form $\log \tau = A - Bw$. τ-w curves for each of the sampling site specimens are included in the respective sampling site sections of the appendix.

Table 12: Physicochemical Test Data

59. The information in Table 12 summarizes the soil pH, total CEC, and the amounts of the exchangeable soil cations for the soil specimens. The pore fluid cations have been determined and are tabulated. Two indices, the exchangeable sodium percentage (ESP) and sodium absorption ratio (SAR), which reflected the characteristics of the exchangeable soil and pore fluid cations, respectively, have been calculated and tabulated.

Table 13: Mineralogy Data

60. The information in Table 13 summarizes in a semiquantitative sense the clay mineralogy and accessory mineral constituency of the tested specimens from each of the sampling sites. The data indicate that the overall mineralogical composition of the test specimens was diverse and that most of the samples contained a complex mineralogical suite. The diversity is demonstrated by the fact that only two samples had two or less clay mineral types in the clay mineral suite and that approximately half of the samples contained five or more accessory mineral constituents.

Table 11

Summary of Soil Moisture Suction Data

Site No.	w Moisture Content %	τ* Soil Suction tsf	τ-w Equation Coefficients** A	B
1	42.8	4.77	5.214	0.1068
2	26.7	2.12	3.740	0.1345
3	49.7	0.32	3.661	0.0880
4	24.6	0.53	2.918	0.1152
5	22.7	1.80	2.677	0.1039
6	13.5	4.34	10.915	0.7707
7	15.8	0.32	6.221	0.3936
8	15.1	0.37	8.512	0.5274
9	10.9	18.42	3.192	0.1880
10	17.4	30.58	5.831	0.2454
11	9.1	23.82	2.480	0.1205
12	26.6	1.80	4.594	0.1601
13	17.2	2.86	6.400	0.3386
14	25.7	7.83	2.972	0.0811
15	38.0	1.80	6.453	0.1620
16	15.2	16.41	5.819	0.3140
17	26.9	3.92	4.422	0.1507
18	15.5	30.69	6.592	0.3321
19	17.9	1.27	6.203	0.3386
20	33.8	2.01	6.916	0.2107

* Total soil suction at natural moisture content.

** $\log \tau = A - Bw$.

Table 12

Summary of Physicochemical Test Data

Site No.	Soil pH	Cation Exchange Capacity meq/100 g	Exchangeable Soil Cations* Na	Ca	Mg	K	Exchangeable Sodium Percentage %	Pore Fluid Cations Na	Ca	Mg	K	Sodium Adsorption Ratio
1	6.3	52.8	4.0	28.9	14.2	1.1	7.6	0.1	1.2	0.8	4.4	0.1
2	4.8	33.6	0.2	9.6	6.9	0.5	0.6	Trace*	70.1	Trace*	Trace*	0.0
3	5.7	53.6	1.2	21.3	13.2	1.2	2.2	0.2	1.0	0.7	1.5	0.2
4	7.7	21.5	0.9	27.0	2.3	0.2	4.2	Trace*	1.7	0.3	2.5	0.0
5	8.1	44.5	2.1	59.0	5.9	0.4	4.7	Trace*	1.1	0.2	2.2	0.0
6	7.8	17.0	6.4	25.0	6.6	0.2	37.7	0.4	12.2	9.8	37.7	0.1
7	7.0	45.2	1.3	29.4	9.8	1.4	2.9	0.1	2.2	0.9	2.9	0.1
8	8.2	13.5	0.3	7.9	12.0	0.7	2.2	Trace*	0.4	1.8	1.2	0.0
9	8.9	30.6	3.8	39.7	5.1	0.5	12.4	Trace*	0.5	0.2	5.5	0.0
10	8.1	79.3	24.0	64.1	8.8	0.5	30.3	0.2	11.0	3.2	46.4	0.1
11	8.4	16.7	15.1	78.0	3.6	0.9	90.4	0.8	10.2	6.3	101.4	0.3
12	6.9	31.0	2.1	9.0	14.6	1.0	6.8	11.4	8.5	5.0	0.5	4.4
13	6.9	24.8	0.5	50.4	6.8	0.3	2.0	5.1	36.9	11.7	0.6	1.0
14	7.7	22.7	5.7	11.8	23.7	0.9	25.1	40.7	22.7	28.2	1.5	8.1
15	6.7	48.1	3.0	17.1	9.3	0.8	6.2	6.6	2.8	0.8	0.3	4.9
16	8.2	25.0	1.8	19.3	9.1	0.3	7.2	7.8	4.2	2.1	Trace*	4.4
17	5.2	34.0	3.8	16.8	13.2	0.6	11.2	32.7	25.0	16.4	1.1	7.2
18	5.9	32.9	4.7	13.7	10.8	1.1	14.3	18.9	9.1	2.7	0.4	7.8
19	8.1	36.0	0.4	25.4	15.8	0.9	1.1	2.3	24.4	9.4	1.3	0.6
20	7.5	40.7	3.6	45.5	16.6	1.2	8.9	13.8	28.3	13.7	0.7	3.0

Note: Na = sodium, Ca = calcium, Mg = magnesium, K = potassium.
* Trace - detectable but not measurable.

Table 13

Clay Mineralogy and Accessory Mineral Constituents

Site Number	Montmorillonite	Chlorite	Vermiculite	Clay-Mica	Kaolinite	Quartz	K-Feldspar	Plagio-Feldspar	Calcite	Dolomite	Hematite	Magnatite	Goethite	Gypsum
1	COM	ND	ND	MIN	MOD	MOD	MIN	ND	ND	ND	ND	ND	RARE	ND
2	COM	ND	ND	MIN	MOD	COM	ND	ND	ND	ND	ND	RARE	ND	ND
3	MOD	MIN	ND	MOD	MOD	MOD	ND	MIN	ND	ND	ND	RARE	ND	ND
4	MOD	ND	MIN	MOD	MOD	COM	ND	MIN	MOD	ND	MIN	RARE	ND	ND
5	ABU	ND	ND	ND	ND	MOD	ND	MIN	COM	ND	ND	ND	ND	ND
6	ND	MOD	ND	MOD	MIN	COM	ND	MIN	ND	ND	MIN	RARE	ND	COM
7	MOD	MIN	ND	MOD	MOD	MOD	ND	MIN	ND	ND	ND	RARE	ND	ND
8	MIN	MOD	ND	MOD	MIN	COM	MIN	MOD	MOD	MIN	MIN	RARE	ND	ND
9	COM	MIN	ND	MOD	MOD	COM	MIN	MOD	MOD	ND	MIN	RARE	ND	ND
10	ABU	ND	ND	ND	MOD	COM	ND	ND	MOD	ND	MIN	RARE	ND	ND
11	MIN	MIN	ND	MOD	MOD	COM	MIN	MIN	MOD	MIN	ND	RARE	ND	MOD
12	ABU	ND	MIN	MIN	MOD	COM	MIN	MIN	ND	ND	ND	RARE	RARE	ND
13	COM	ND	ND	MIN	RARE	MOD	ND	RARE	COM	ND	ND	ND	ND	RARE
14	COM	MOD	ND	MOD	MIN	COM	ND	MOD	ND	MIN	ND	RARE	ND	MIN
15	ABU	ND	ND	RARE	MIN	COM	RARE	RARE	ND	ND	ND	RARE	ND	ND
16	COM	ND	MIN	MIN	MIN	COM	MIN	MOD	MIN	RARE	ND	RARE	ND	ND
17	ABU	ND	ND	MIN	MOD	COM	ND	MIN	ND	ND	ND	RARE	ND	MIN
18	ABU	ND	RARE	MIN	MIN	COM	ND	MOD	ND	ND	ND	RARE	ND	ND
19	ABU	MIN	ND	MIN	MIN	MOD	ND	MIN	ND	MIN	ND	RARE	ND	ND
20	MOD	RARE	ND	RARE	RARE	MOD	ND	MIN	RARE	RARE	ND	RARE	MIN	MIN

Note:

Amount of Mineral	Descriptor
$\geq 50\%$	Abundant → ABU
25% to 50%	Common → COM
10% to 25%	Moderate → MOD
5% to 10%	Minor → MIN
$\leq 5\%$	Rare → RARE
0	None Detected → ND

Scanning election microscopy

61. The SEM photographs were not quantitatively summarized; instead, the SEM photographs are presented for each of the sampling sites in the respective sections of the appendix. The purpose of this portion of the investigation was to identify clay microfabrics and to attempt to classify the samples on the basis of their internal particle arrangement. The term microfabric refers to the geometrical orientation of the constituent grains in space and to certain aspects of microtexture such as void space and grain size.

62. Clay fabrics may be classified into two rather broad categories on the basis of clay platelet orientation. One category, face-to-face (dispersed), refers to orientations in which the contacts between individual platelets are along platelet faces, which results in the parallel vertical orientation of the c-crystallographic axes of the individual platelets. This fabric is typical of overconsolidated clay shales and is partially responsible for the development of fissility in some shales. The second category, edge-to-face (flocculated), is a random orientation of the platelets and their c-axes whereby contact between platelets involves edges and faces. This type of fabric is present in the more massive shales and mudstones.

63. The type of fabric exhibited by a particular argillaceous rock is a function of the loading or consolidation history, as previously mentioned, and is also dependent on such factors as grain size, type of clay mineral, presence or absence of cements or organic materials, and environment of deposition.

64. The two fabric types previously described are two rather simplistic end members of several possible platelet arrangements. In other words, for many argillaceous materials, it is not possible to describe the fabric as either face-to-face or edge-to-face because the material may exhibit a fabric somewhere in between the two extremes. Also, in some cases argillaceous materials may exhibit a face-to-face fabric in which the platelets occur in a wavy orientation resulting in nonalignment of the c-axes. The occurrence of domains in which a particular fabric dominates and is separated from other similar domains by

areas exhibiting a different fabric is another problem in classifying the fabric of some materials.

65. The identification of fabric type is dependent on the perfection of end member development and the method of observing the fabric. Visual determination of a shale as being fissile will almost by definition indicate that the shale exhibits a well developed face-to-face fabric. On the other hand, the more massive argillaceous rocks require more sophisticated techniques such as binocular and petrographic microscopy or SEM techniques. The SEM is a useful method for studying the internal organization of argillaceous materials for several reasons, namely:

- a. The SEM can be operated on a wide range of magnifications beginning where the petrographic microscope ceases to be effective (approximately ×100) and extending up to ×20,000 or so depending on the type of instrument.
- b. The depth of focus is large.
- c. The SEM provides considerably more information on size and distribution of pore space than light microscopes.

66. The key to qualitative identification of fabric is the determination of the relative number of platelet faces versus edges in the two sample orientations (Figure 8). The face-to-face orientation in an overconsolidated clay shale will be evident by the lack of or total absence of edges in specimens cut normal to the vertical or y-axes. In this view, platelet faces will predominate. On the other hand, a mudstone having a random clay platelet orientation will exhibit both edges and faces in both views.

67. With this in mind the specimens from the 20 sampling sites were viewed through the SEM and photographs were taken of areas which appeared to be representative of the total specimen. The specimens were examined at magnifications ranging from a few hundred up to several thousand; however, previous experience has shown that magnifications between 600 to 800 and 2000 to 3000 are most meaningful for fabric studies. These magnification ranges are recommended because lower magnification does not provide sufficient detail and higher magnification may concentrate areas which are not typical of the specimen. The photographs

shown in the appendix were taken at magnifications of 650 and 2300. An approximate scale for the estimation of particle sizes is:

×650	0.25 inch ≈ 10 μm
×2300	0.90 inch ≈ 10 μm

68. Examination of the SEM photographs from the 20 sampling sites was directed toward the identification of five compositional and fabric elements, which include:

(1) Clay mineral platelets
(2) Platelet orientation
(3) Void space
(4) Microfractures
(5) Accessory mineral constituents

The SEM photo examination resulted in the categorization of the samples into five groups based upon consideration of these five elements. The groups are defined and discussed in the following paragraphs:

a. Group 1. This group consists of samples from sites 1, 12, 15, 18, and 20. The group is characterized by well developed face-to-face (dispersed) fabrics as indicated by the lack of exposed edges in the views normal to the y-axes and the predominance of exposed edges in the views normal to the x-axes. Individual clay mineral platelets were evident in each sample. Void space and microfractures were present in some of the samples.

b. Group 2. This group consists of samples from sites 3, 5, 7, 8, 9, 11, 14, 17, and 19. The face-to-face or dispersed fabric was also characteristic of this group; however, it was not as well developed as that of Group 1. Group 2 exhibited a somewhat wavy stratification which resulted in the appearance of both edges and faces in both views. Void space and microfractures were not common in any of the specimens.

c. Group 3. This group consists of samples from sites 2 and 4. These two samples did not appear to possess significant platelet orientation as indicated by the absence of platelet alignment and the appearance of edges and faces in both views. Void space was high in both samples.

d. <u>Group 4.</u> This group consists of samples from sites 6 and 13. This group is characterized by a rather massive appearance and the absence of good particle orientation. The sample from site 13 exhibited relatively abundant amounts of accessory mineral constituents, probably calcite.

e. <u>Group 5.</u> This group consists of samples from sites 10 and 16. Both samples, but particularly the site 10 sample, exhibited distinct aggregation of clay platelets into domains. The domains consisted of apparently well oriented platelets. Both samples exhibited considerable void space between domains.

69. Although the above categorization is somewhat subjective, it constitutes a valuable attempt to qualify the fabric of these materials and may prove extremely useful in the following section of the report.

ANALYSIS OF RESULTS

70. The phenomenological approach to the verification of the natural microscale mechanisms was briefly described earlier as an attempt to define the role of the microscale mechanisms by observing the macroscale volume change behavior and correlating it with measurable parameters which generally reflect basic characteristics of the mechanisms. For example, the amount of expansion is dependent on the composition of the soil or more precisely the amount and type of clay mineral present. The total CEC is a measurable parameter which generally correlates with the type of mineral present and reflects a characteristic of the clay particle attraction mechanism since it is a measure of the clay's ability to hold cations and molecules such as water. The number of relationships between microscale mechanisms, measured variables, and macroscale volume change behavior on which at least a partial understanding has been developed are limited. Examples of these relationships are summarized in Table 14. As indicated in Table 14, the measured variables are limited to physicochemical properties. The laboratory testing program previously described was designed to gather as many physical, physicochemical, and mineralogical parameters as feasible for comparison with measured volume change and suspected correlations with microscale mechanisms. Because of the large amount of data available on samples from the 20 sampling sites, it was necessary to apply some statistical comparison procedures to help highlight the better correlations.

Description of Statistical Comparison Procedures

71. The statistical comparison procedures involved a simple linear regression analysis of two dependent variables (measured swell and swell pressure) and 35 independent variables. The independent variables included the remaining measured physical, physicochemical, and mineralogical variables as well as some published combination of variables. Higher order comparisons were not attempted since the purpose of

Table 14

Relationships Between Microscale Mechanisms, Measured Variables, and Volume Change

Microscale Mechanism	Measured Variable	Influence on Volume Change
Clay particle attraction	Cation exchange capacity (CEC)	CEC is a measure of the clay particle's surface reactivity or affinity for attracting and orienting water (i.e. double layer water). Increasing CEC generally indicates the presence of active clay minerals (Montmorillonite, etc.) thus more volume change
Cation hydration	Cation exchange capacity	Same basic influence as described above; however, the type of cation present is of more concern
	Exchangeable cations	Measure of the type and amount of cations present on the clay mineral. The thickness of the water layer and the orientation of the water molecules vary with the type of cation. For sodium the thickness is large with decreased orientation. For calcium the thickness is less than for sodium but the orientation is better
Osmotic repulsion	Exchangeable cations and pore fluid cations	The greater the difference of cation concentrations in the double layer water and the pore water the greater the volume change from osmotic repulsion

the statistical analysis was not to develop equations but simply to point out the better comparisons using the correlation coefficient, r. The correlation coefficient, r, is a measure of the mutual relationship between two variables (dependent and independent). More precisely, r is a measure of the degree of closeness of the linear relationship between two variables. The r always lies between -1 and +1, with positive r values indicating that both variables are increasing. Negative r values indicate that one variable is increasing while the other is decreasing. To even be considered as a useful r value for r^2 comparison purposes, the r should be greater (or less) than +0.7 (-0.7) with the better values being closer to ± 1.

72. The independent variables used in the statistical comparisons are summarized in Table 15. The statistical comparisons were made between the dependent and independent variables for all 20 sites. In addition, two categorical subgroupings of the 20 sites were used in the comparisons. One subgrouping was based on physiographic location of the sampling site as defined in Reference 26. Based on information in Reference 26, three major subgroups were defined, namely:

Atlantic and Gulf Coastal Plains Subgroup--sites 1, 2, 3, 4, and 5

Colorado Plateau Subgroup--sites 9, 10, and 11

Great Plains Subgroup--sites 6, 7, 8, and 12 through 20

The second subgrouping was based on climate as rated by the Thornthwaite Moisture Index (TMI) using the 5-year average value of TMI between 1970 and 1974. Using this procedure, four major subgroups were defined, namely:

Humid Subgroup (TMI > 20)--sites 1, 2, 3, and 4

Moist Subhumid Subgroup (0 < TMI < 20)--sites 5, 7, 8, 12, and 13

Dry Subhumid Subgroup (-20 < TMI < 0)--sites 6 and 14 through 20

Semiarid Subgroup (-40 < TMI < -20)--sites 9, 10, and 11

Since the Colorado Plateau physiographic subgroup and the semiarid climatic subgroup contain the same sampling sites, the total amount of subgroups for comparison purposes is six. It should be kept in mind that

Table 15

Summary of Independent Variables Used in Statistical Comparisons

Variable	Description
w_i(OST)	Initial moisture content from overburden swell test, %
γ_i(OST)	Initial dry density from overburden swell test, pcf
e_i(OST)	Initial void ratio from overburden swell test, dim
w_i(CVSP)	Initial moisture content from constant volume swell pressure test, %
γ_i(CVSP)	Initial dry density from constant volume swell pressure test, pcf
e_i(CVSP)	Initial void ratio from constant volume swell pressure test, dim
%-200	Percent minus No. 200 sieve
%-2μm	Percent minus 2 micrometer (percent clay)
LL	Liquid limit, %
PL	Plastic limit, %
PI	Plasticity index, %
Activity	Ratio of PI to % - 2μm
LI	Liquidity index $(w_{nat} - PL)/PI$
PR	Plasticity ratio, PI/PL
SL	Shrinkage limit, %
SR	Shrinkage ratio
SI	Shrinkage index, LL - SL
BLS	Bar linear shrinkage, %
τ_{net}	Soil suction (tsf) at natural moisture content
A	Y-intercept of soil suction versus water content plot
B	Slope of soil suction versus water content plot
C_τ	Soil suction index, $\Delta e/\Delta\tau$
pH	pH of the natural material
CEC	Cation exchange capacity, milliequivalents/100 g
ΣEC	Summation of exchangeable cations, milliequivalents/100 g
ESP	Exchangeable sodium percentage, %
ΣPFC	Summation of pore fluid cation, milliequivalents/litre
SAR	Sodium absorption ratio
% Mont	Percent montmorillonite
TMI	Thornthwaite moisture index
w_i/PL	Ratio of w_i(OST) to plastic limit
w_i/LL	Ratio of w_i(OST) to liquid limit
A - (B · PL)	Sum of indicated variables
A/B	Ratio of indicated variables
CE activity	Cation exchange capacity/percent minus No. 200 sieve

comparisons based on data from all 20 sites are in a small data group from a statistical standpoint, and subgrouping a small data group requires caution in interpreting the correlation coefficients.

Results of Statistical Comparisons

73. Statistical comparisons between the macroscale volume change characteristics and the three soil suction parameters, i.e. soil suction at natural water content and the A and B parameters from the soil suction versus water content relationships, did not correlate when all 20 sampling sites were analyzed as one group. However, when grouped according to physiographic or climatic subgroups, five of the six subgroups had r values greater than 0.7 with at least one of the three parameters. The correlation coefficients with swell as the dependent variable are:

	τ_{nat}	A	B
Atlantic and Gulf Coastal Plains (N = 5)	0.94	0.89	--*
Colorado Plateau (N = 3)	0.73	0.99	0.96
Great Plains (N = 12)	0.77	--*	--*
Humid (N = 4)	0.96	0.94	--*
Moist Subhumid (N = 5)	--*	0.71	0.82
Dry Subhumid (N = 8)	0.51	--*	--*
Semiarid (N = 3)**	0.73	0.99	0.96

* Values $-0.5 < r < +0.5$ not recorded.
** Same as Colorado Plateau.

The value of N indicates the number of data points in the subgroup. The correlation coefficients using swell pressure as the dependent variable are approximately the same with the trend being toward slightly smaller values.

74. The significance of these correlations between macroscale volume change and soil suction and the A and B parameters is twofold: (a) soil suction appears to be a measurable variable that correlates with macroscale behavior and combines the influence of the microscale

mechanisms as previously described, and (b) volume change and soil suction are interrelated with physiography and climate.

75. Although beyond the scope of this research task, statistical comparisons between the macroscale volume change and the measured independent variables were examined on a preliminary basis with a view toward identification/classification techniques. These comparisons did not indicate many correlations. In fact, these comparisons between volume change (swell and swell pressure) and independent variables for all 20 sampling sites resulted in one correlation coefficient, r, greater than 0.5 for each dependent variable and that was with the same independent variable, namely the plastic limit. Between measured swell and plastic limit, r was equal to 0.54 and between measured swell pressure and plastic limit, r was equal to 0.56. For the six subgroups (in order of listing) with measured swell as the dependent variable, the r values were 0.47, 0.89, 0.66, 0.48, 0.09, and 0.73, respectively. In the humid climatic subgroup where the r value for plastic limit dropped to 0.09, the r value for liquid limit was 0.95. From a statistical standpoint all of the above correlations can be disputed on the basis of either small r values or small sample size; however, on a mathematical comparison basis, these values indicate that the Atterberg limits are still one of the better working tools the engineer has for identifying swell potential. Implications of the lack of correlations between macroscale volume change and the measured independent variables concerning the validity of various indirect techniques for identification/classification of potentially expansive soils, previously summarized,[1] are beyond the scope of this task and will be dealt with in a subsequent task.

Results of Comparisons with Soil Suction Data

76. It was pointed out earlier that the total soil suction consists of two components, namely, matrix and osmotic suctions. In addition, the literature review has shown that the matrix component represents the influence of the clay particle attraction and cation hydration mechanisms and the osmotic component represents the osmotic repulsion

mechanism. It should be pointed out that no method exists for qualitatively or quantitatively separating the combined influence of the clay particle attraction and cation hydration mechanisms since they are so interdependent on one another. From a practical standpoint, the two mechanisms essentially act as a single influence. Finally, it has previously been described that the thermocouple psychrometer technique generally measures the matrix component of soil suction when developing the soil suction versus water content relationship; however, an osmotic component may be evaluated if the soil suction versus water content relationship becomes horizontal. The osmotic component tends to be dominant at high water contents and may be estimated as the soil suction at the higher water contents when the matrix suction becomes negligible. When an osmotic component is indicated in the soil suction versus water content relationship, the matrix suction may be obtained by subtracting the osmotic component from the soil suction value shown for a specific water content.

77. Examination of the total soil suction versus water content curves for the 20 sampling sites shows that the osmotic component of soil suction is usually very small (less than 1 tsf) or essentially nonexistent. This is evidenced by the fact that the smallest measured soil suction values are less than 1 tsf (generally less than 0.5 tsf) using the psychrometric technique. Two exceptions to this trend are sites 11 and 14 for which the smallest soil suctions measured were 9.2 and 3.5 tsf, respectively. Therefore, the observed curves reflecting the measured matrix suction actually represent the total soil suction.

78. The fact that there was no significant osmotic component of soil suction, with the exception of the two sites mentioned above, agrees with the physicochemical analysis of the specimens. Results of the analysis indicate that 15 of the 20 sampling sites had ratios of the summation of pore fluid cations to summation of exchangeable cations (Σ PFC/Σ EC) less than one. The five sampling sites with ratios greater than one were sites 11 and 14, as mentioned above, plus sites 2, 6, and 17. The physicochemical testing results are significant from the double-layer theory standpoint since movement of cations into the double

layer will not normally occur, which is the cause of osmotic repulsion, unless the pore fluid cation concentration is greater than the cation concentration in the double-layer water (exchangeable cations).

79. Since no significant osmotic component of soil suction was measured for a majority of the samples tested and since the samples represent a diverse cross section of typical expansive materials in the United States, the obvious conclusion concerning the osmotic repulsion mechanism is that it is basically insignificant for these materials and the range of moisture contents tested. If the materials from sites 11 and 14 were located in a climatic region or ambient environment more conducive to higher natural moisture contents, then volume change resulting from osmotic repulsion would be of more consequence.

80. The previous discussions concerning osmotic repulsion and the inherent difficulty in obtaining the individual influence of clay particle attraction and cation hydration essentially reduce the number of microscale mechanisms which cause volume change to one combined influence, namely clay particle attraction and cation hydration. In other words, for the materials tested, the clay particle attraction mechanism plays the major role in determining the volume change behavior. Second in order of influence, but actually showing a combined effect with the clay particle attraction, is the cation hydration. The mechanism showing the least influence on the materials was the osmotic repulsion mechanism.

SUMMARY

81. This report, which summarizes the basic principles involving the causes of volume change (microscale mechanisms), defines the basic definitive relationships associated with soil suction, and evaluates an extensive laboratory testing program, provides an insight into the relative roles of the microscale mechanisms in determining volume change characteristics. Some of the more important points concerning the research task and the roles of the mechanisms are summarized in the following paragraphs.

82. Although some interesting trends may be inferred using the approach, it is still not successful to infer the microscale mechanism influence from observed macroscopic volume change behavior.

83. Total soil suction, which is the combination of the matrix and osmotic components, reflects the influence of the three major microscale mechanisms. The matrix suction represents the clay particle attraction and cation hydration mechanisms, which in reality act as one influence since they are so interrelated. The osmotic suction represents the osmotic repulsion mechanism.

84. The measurement of soil suction using the thermocouple psychrometer technique is simple, quick, and accurate. The results of the measurements represent a characteristic of the material which can be related to volume change using relatively simple relationships.

85. The results of the laboratory testing program indicated that no significant osmotic component of soil suction was measured on 18 of the 20 samples. In the two exceptions (sites 11 and 14) the osmotic component became significant at the higher moisture contents; i.e., 140 and 125 percent, respectively, of the natural moisture content.

86. Analysis of the results indicates that for the materials and range of moisture contents tested, the clay particle attraction and cation hydration microscale mechanisms play the greatest role in causing volume change. At higher moisture contents and higher cation concentration environments, the osmotic repulsion mechanism provides a secondary influence on volume change behavior.

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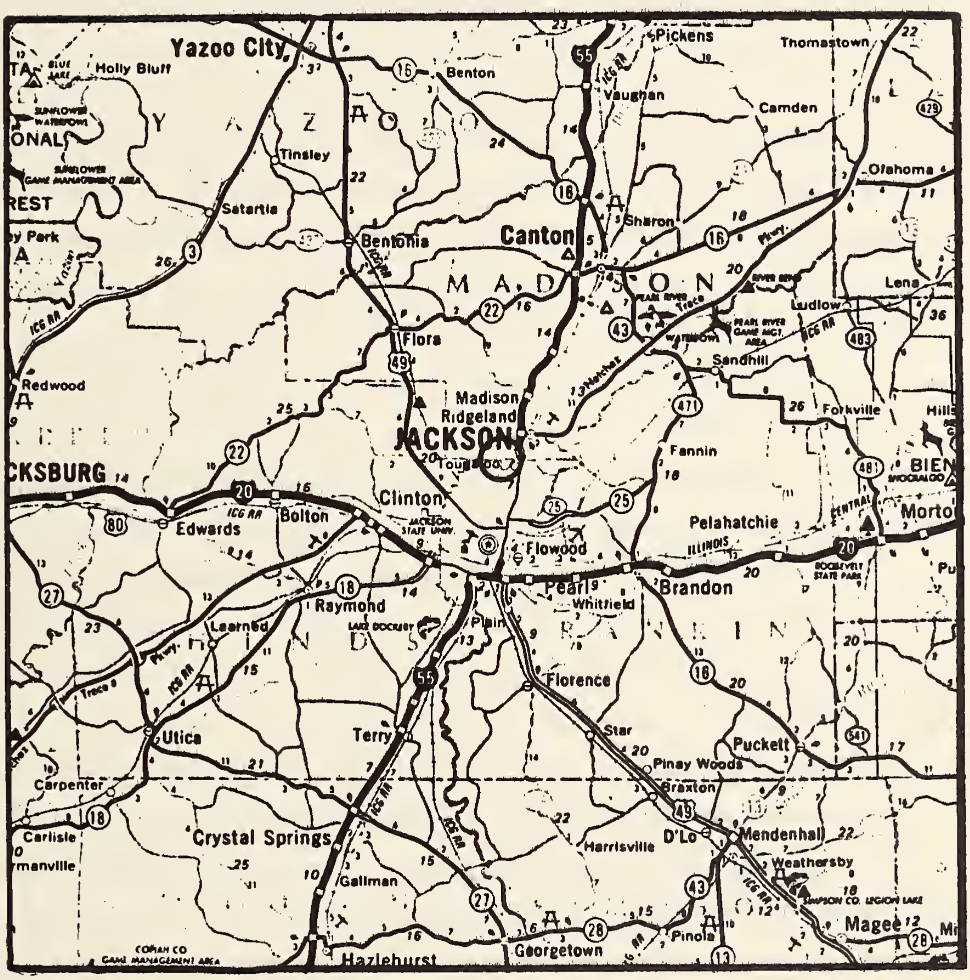
APPENDIX

SAMPLING SITE NO. 1, JACKSON, MISS.



Site Location Information

1. Sampling site No. 1 is located in central Mississippi near the north city limit boundary of Jackson, Miss. City limit boundary of Jackson, Miss., coincides with Hinds-Madison County boundary and County Line Road. The site is located approximately 1.75 miles southwest of I-55 and I-220 junction. The field-monitoring section begins at east approach and continues eastward from junction of I-220 and County Line Road. Samples taken at station 686+00 at approximate centerline of westbound lane. (G.S. el = 357.4 ft.)

Site Description

2. Sampling site is located in a cut section ($\approx$ 12 ft) in gently rolling terrain. Drainage is in a southeasterly direction over a gentle to moderate slope. Surrounding area has a complete grass cover and nearly total tree cover.

Site Geology

3. Sampling site is situated on the East Gulf Coast Plain Section of the Coastal Plain Physiographic Province, an area of relatively low relief. The samples were taken from the marine Yazoo Formation of the Jackson Group, Upper Eocene Series, Tertiary System. The Yazoo Formation is overlain by the Forest Hill Formation (Oligocene) and underlain by the Moodys Branch Marl. The Yazoo Formation consists of 90-600 ft of massively bedded calcareous clay with some interbedded lignite, bentonite seams, and sand. The upper few tens of feet are usually oxidized and exhibit a reddish hue in outcrops. The outcrop area extends generally across the State from Wayne County on the east to Yazoo County on the west. The central area from Jackson, Miss., to Newton County has exhibited the most serious expansive problem.

Sample Description

4. The Yazoo Formation at Jackson, Miss., is a moderately hard, relatively unweathered, pale olive (10 Y 6/2) clay stone with small voids and few open fractures and showing no distinct bedding in hand samples. Surfaces of samples occasionally exhibit black manganese or brownish iron oxide stains. The samples taken were not calcareous although locally the formation exhibits noncontinuous calcareous layers. The SEM photographs show a well-developed, face-to-face particle orientation lacking fractures and void space.

Description of Climate

5. In its broader aspects the climate of Mississippi is determined by the huge land mass to the north, its subtropical latitude, and the Gulf of Mexico to the south, but modifications are introduced by the varied topography. A triangular area, comprising nearly one third of the State, with its apex in Rankin County and its base on the coast, is composed of rolling hills at elevations between 200 and 500 ft above

sea level. The "Delta" region in the northwest extends from the Yazoo-Tallahatchie River system westward to the Mississippi River. In the northeast the land is primarily upland prairie. Between the Delta and the upland prairie the land is broken by a series of ridges and valleys which are oriented in a general southwest-northeast direction. These extend from the Tennessee border to the lower Mississippi River.

6. The prevailing southerly winds provide a moist semitropical climate, with conditions often favorable for afternoon thunderstorms. When the pressure distribution is altered to bring westerly or northerly winds, periods of hotter and drier weather interrupt the prevailing moist conditions. The high humidity combined with hot days and nights in the interior from May to September produces discomfort at times. The principal relief is by thunderstorms, sometimes accompanied by locally violent and destructive winds.

7. In the colder season the State is alternately subjected to warm tropical air and cold continental air, in periods of varying lengths. However, cold spells seldom last over 3 or 4 days. The ground rarely freezes and then mostly only in the extreme north and only a few inches deep. Although slowly warmed by its southward journey, the cold air occasionally brings large and rather sudden drops in temperature. In winter the Atlantic High is sometimes located far enough west to serve as a barrier to cold air approaching the State. Most frequently this produces a pattern of warm clear weather over the southern part of the State with cold, rainy weather north of the "front," but occasionally the entire State will be under the influence of this subtropical anticyclone.

8. Mean annual precipitation ranges from about 50 in. in the northwest to 65 in. in the southeast. During the freeze-free season, rainfall ranges from 23-25 in. in the Delta to 36-38 in. in the southeast.

9. During the winter the precipitation maximum is centered over the northern and western counties (16-18 in.) with the minimum (13 in.) on the coast. In summer the maximum shifts to the coastal counties (19-21 in.) and the minimum to the Delta counties (9-11 in.). The spring and fall patterns are very similar to the summer pattern. The fall months are the driest of the year, precipitation from about 8-13 in.

Climatic Data Summary

Reporting Station: Jackson Weather Service Office (22-4472-05)

Mean Monthly Temperature and Normal
Monthly Precipitation for Period 1941-70:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature, °F	47.0	49.8	56.1	65.7	72.7	79.4	81.7	81.2	76.0	65.8	55.3	48.9	65.0
Precipitation, in.	4.53	4.62	5.63	4.65	4.38	3.40	4.27	3.59	2.99	2.22	3.87	5.04	49.19

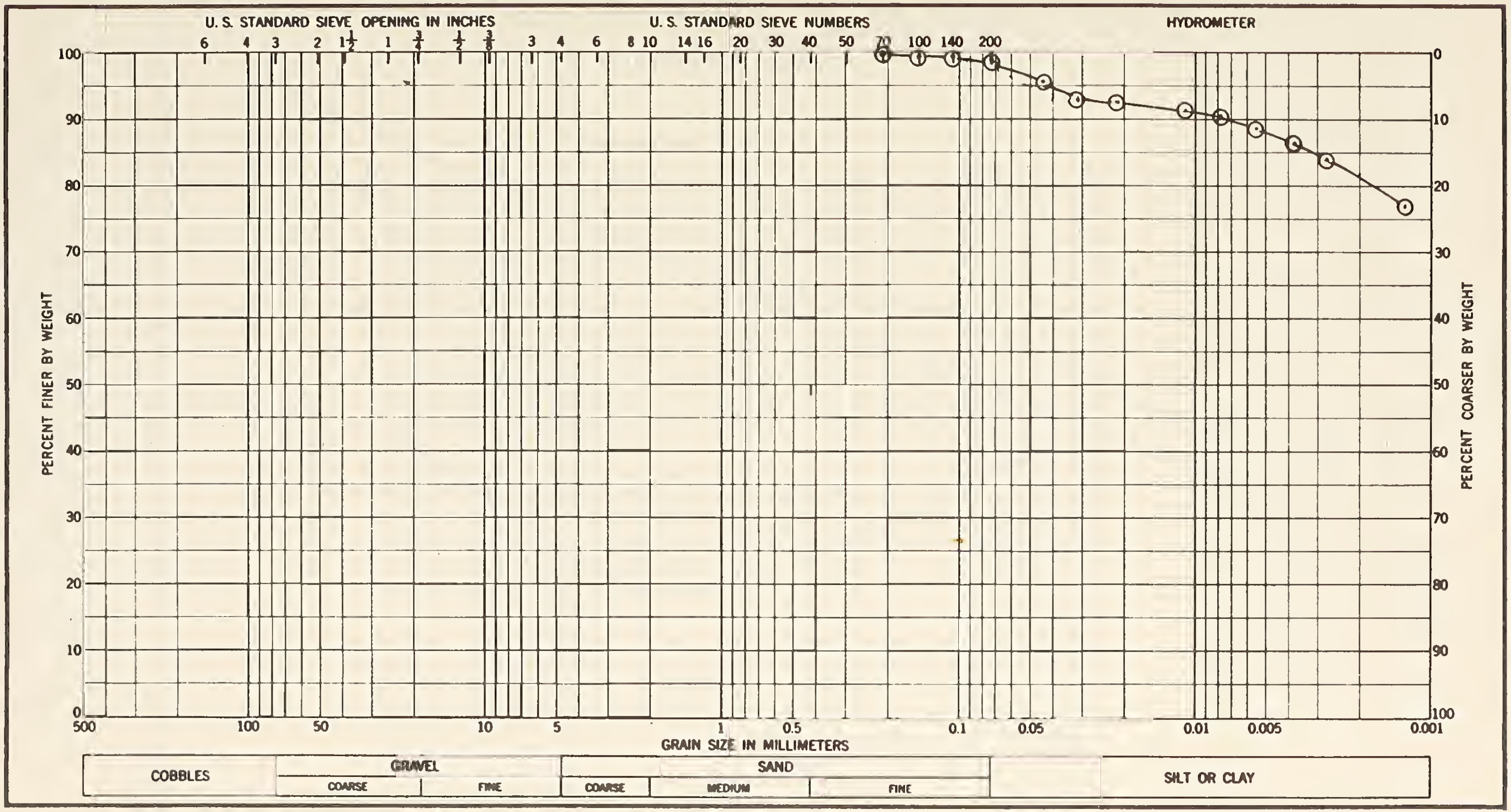
Average Monthly Temperature and
Total Monthly Precipitation for 1971-75:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1971													
Temperature, °F	48.7	49.1	52.4	62.2	67.9	79.9	81.0	80.5	78.3	70.1	54.7	57.9	65.2
Precipitation, in.	3.02	5.68	7.68	6.86	8.05	3.40	6.28	2.64	6.00	0.09	2.54	9.82	62.06
1972													
Temperature, °F	51.5	51.2	58.8	66.4	71.9	79.6	80.4	82.8	81.5	68.0	52.0	50.1	66.2
Precipitation, in.	5.94	3.09	5.57	2.44	4.52	2.01	3.31	2.84	5.04	2.08	3.52	9.67	50.03
1973													
Temperature, °F	44.3	46.9	62.1	62.5	70.9	81.3	83.7	80.1	77.6	68.6	61.7	49.3	65.8
Precipitation, in.	4.59	4.23	6.12	9.44	5.96	0.32	1.99	2.38	4.44	2.72	6.15	6.71	55.05
1974													
Temperature, °F	55.1	50.1	62.4	63.1	73.8	74.8	80.4	79.3	72.0	64.1	55.6	50.4	65.1
Precipitation, in.	11.00	6.72	3.50	6.74	3.01	3.39	1.54	6.17	5.06	1.74	4.12	7.22	60.21
1975													
Temperature, °F	51.8	52.9	56.8	63.5	74.1	78.3	81.2	80.6	72.3	66.2	56.6	47.4	65.1
Precipitation, in.	4.57	6.18	4.86	5.07	6.53	7.44	9.81	6.21	2.68	8.25	4.34	4.29	70.23

Thornthwaite Moisture Index:

1970	1971	1972	1973	1974	1975
57.94	79.83	61.48	91.90	98.16	99.37

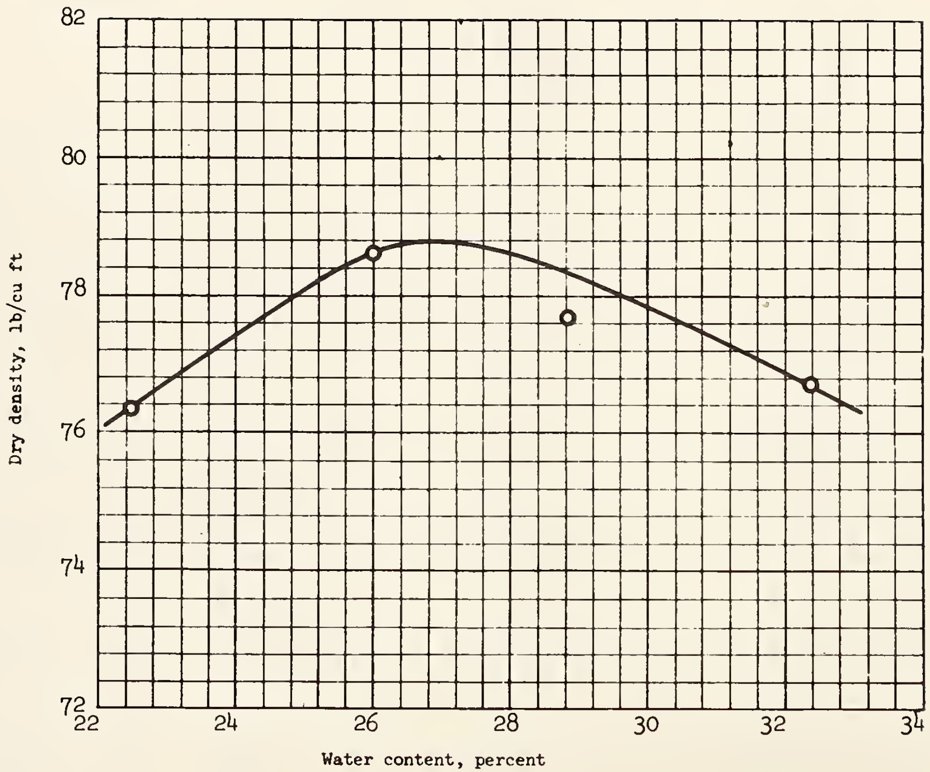
Avg = 81.45



GRADATION CURVE

SITE Jackson, Miss. BORING U-2

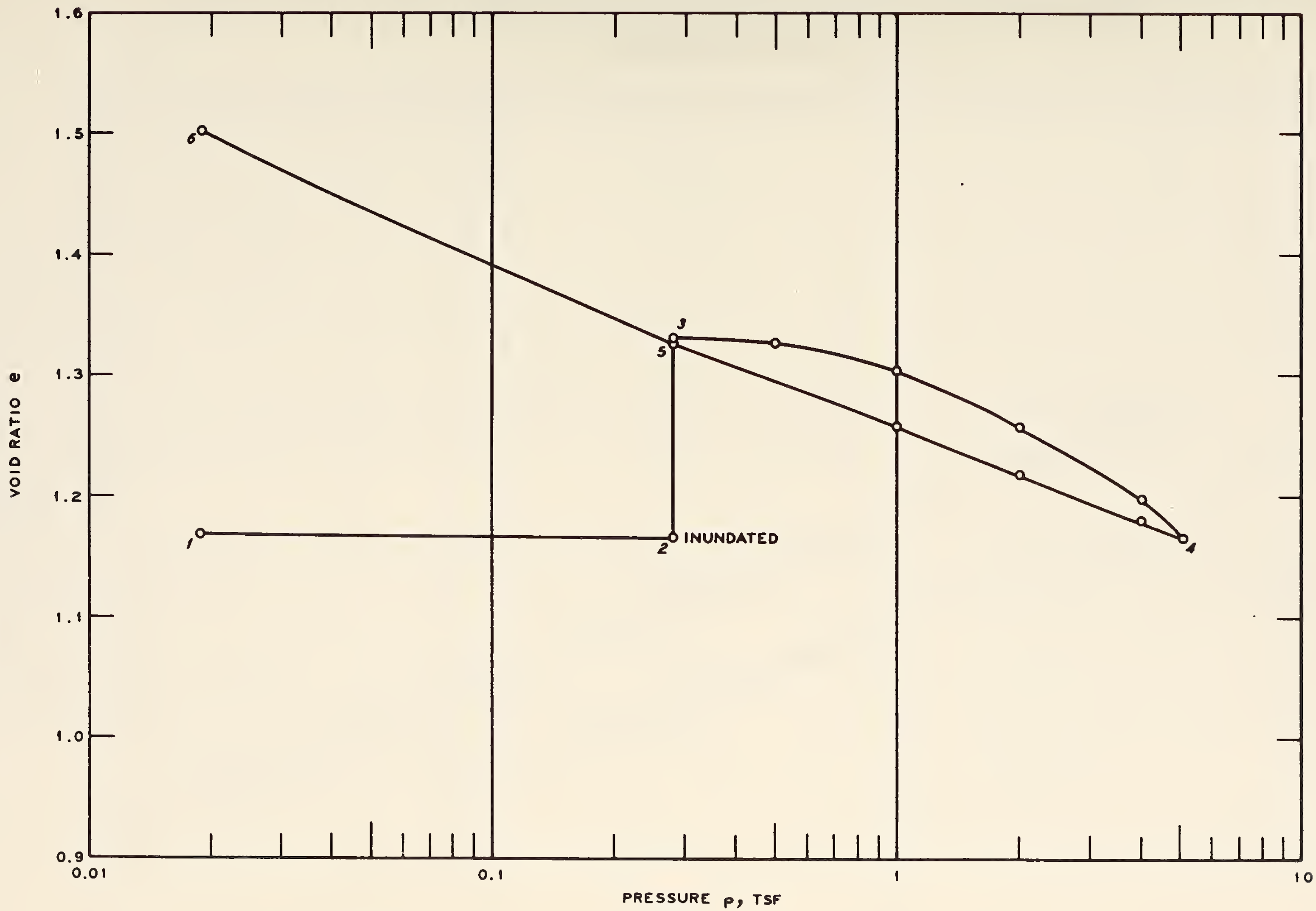
SAMPLE No. 1 DEPTH 1.0-3.2 ft



COMPACTION CURVE

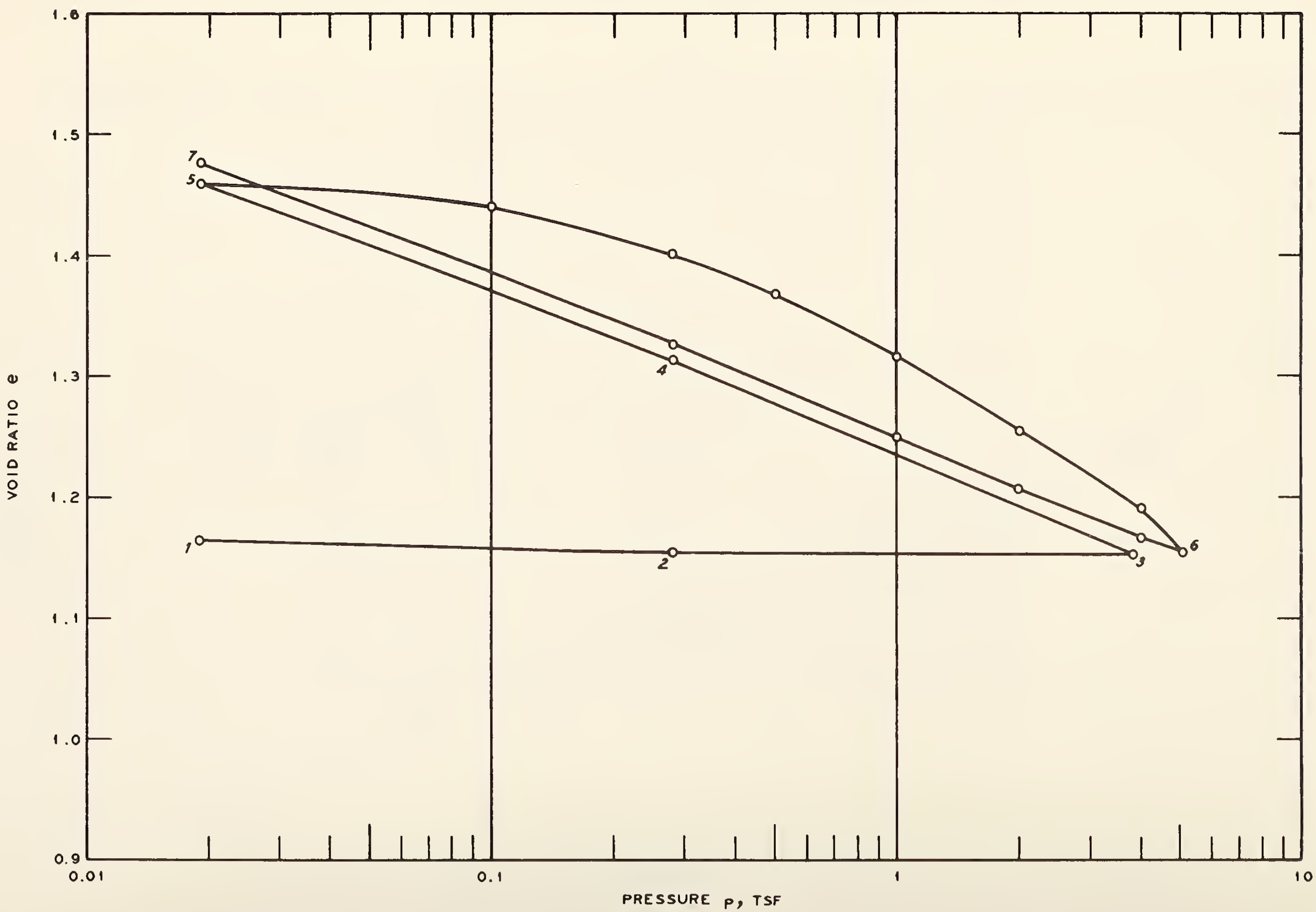
SITE Jackson, Miss.

SAMPLE Disturbed



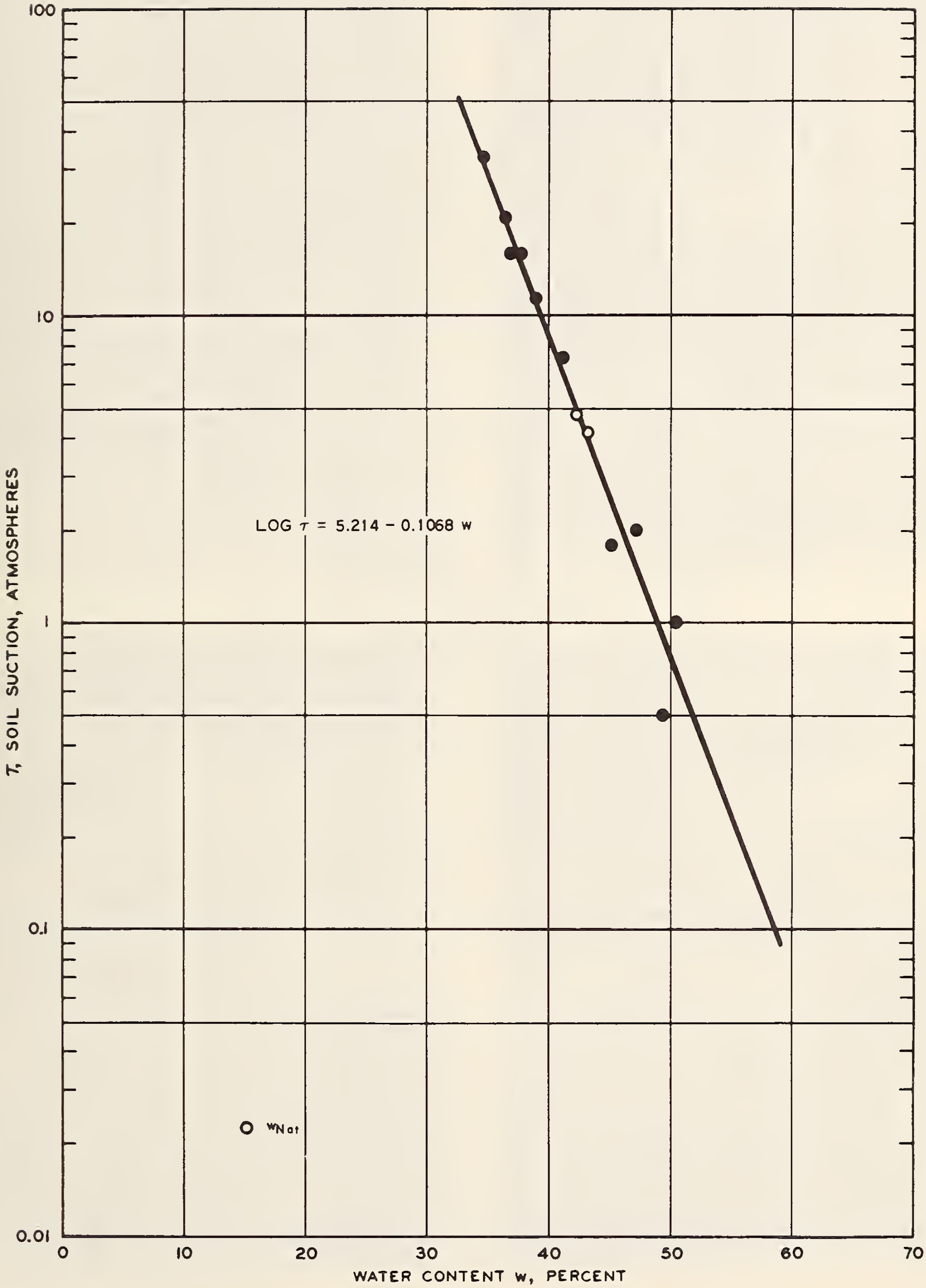
OVERBURDEN SWELL TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

SITE Jackson, Miss. BORING U-2 SAMPLE No. 1 DEPTH 1.0-3.2 ft



CONSTANT VOLUME SWELL PRESSURE TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

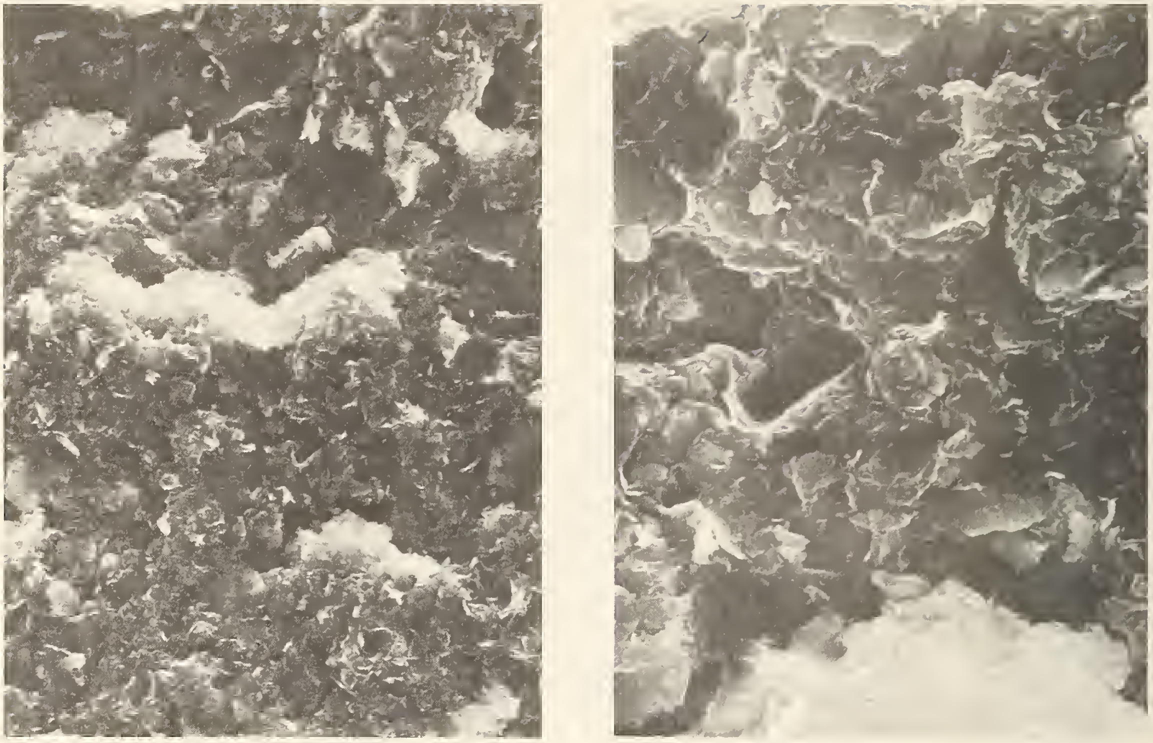
SITE Jackson, Miss. BORING U-2 SAMPLE No. 1 DEPTH 1.0-3.2 ft



SOIL SUCTION VERSUS WATER CONTENT

SITE Jackson, Miss. BORING U-2

SAMPLE No. 1 DEPTH 1.0-3.2 ft



a. Normal to Y, ×650 and ×2300

10 μm

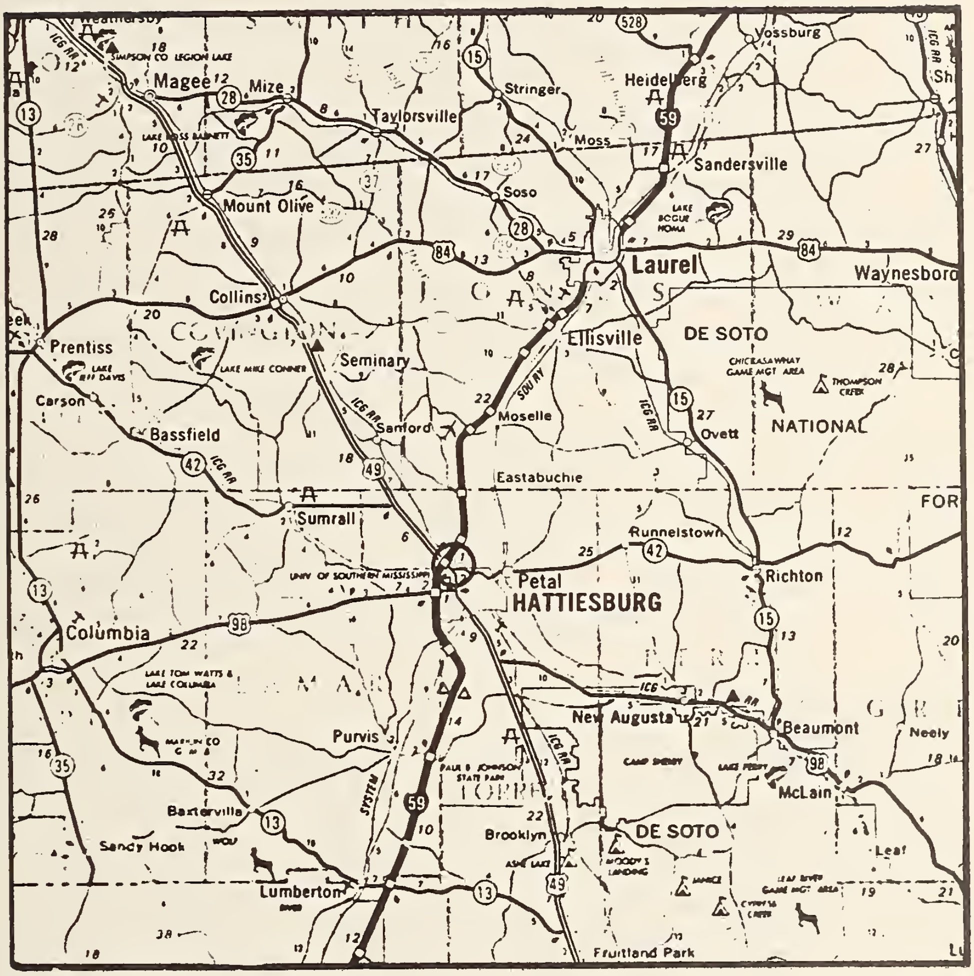
b. Normal to X, ×650 and ×2300

10 μm

SITE Jackson, Miss. BORING U-2

SAMPLE No. 1 DEPTH 1.0-3.2 ft

SAMPLING SITE NO. 2, HATTIESBURG, MISS.



Site Location Information

10. Sampling site No. 2 is located in southeastern Mississippi, in the northwestern portion of the city of Hattiesburg, Miss. The site located approximately 0.8 miles southeast of I-59 and U. S. 49 junction, near the junction of U. S. 49 and Lakeview Drive. Samples were taken in right-of-way adjacent to southbound lane ($\approx$ 70 ft south of centerline) of U. S. 49.

Site Description

11. Sampling site is located at grade in flat to gently rolling terrain. Drainage is in a westerly direction on a gentle slope.

Surrounding area has a partial grass cover and no trees.

Site Geology

12. Sampling site is located in the East Gulf Coastal Plains Section of the Coastal Plain Physiographic Province. The topography is relatively flat although low and rolling hills are locally present. The samples were taken from the Hattiesburg Formation of the Miocene Series, Tertiary System. The Hattiesburg Formation consists of a maximum of approximately 100 ft of massive gray to black clay with some sand stringers overlying the Catahoula (Miocene) sand and underlying the sands of the Citronelle Formation (Pliocene or Pleistocene). The exact stratigraphic relationships between the Hattiesburg clays and the surrounding units is not clear. The Hattiesburg clays appear to occur as continental clayey lenses either grading laterally into or lying unconformably upon sandy facies. The outcrop area of these clays are generally restricted to the Hattiesburg vicinity. Some evidence suggest that these clays are a lateral gradation with the marine facies of the Pascagoula Formation.

Sample Description

13. The Hattiesburg Sample is a hard weathered, mottled moderate red (5 YR 4/6) to pale orange (10 YR 8/2) sandy silty clay. Fractures and void spaces are common and many are stained with iron oxide. The material is noncalcareous and contains a trace of organic material. Bedding is not evident in the disturbed samples. The SEM photographs indicate a generally random particle orientation with considerable voids.

Description of Climate

14. In its broader aspects the climate of Mississippi is determined by the huge land mass to the north, its subtropical latitude, and the Gulf of Mexico to the south, but modifications are introduced by the varied topography. A triangular area, comprising nearly one third of the State, with its apex in Rankin County and its base on the coast, is composed of rolling hills at elevations between 200 and 500 ft above sea level. The Delta region in the northwest extends from the Yazoo-Tallahatchie River system westward to the Mississippi River. In the northeast the land is primarily upland prairie. Between the Delta and

the upland prarie the land is broken by a series of ridges and valleys which are oriented in a general southwest-northeast direction. These extend from the Tennessee border to the lower Mississippi River.

15. The prevailing southerly winds provide a moist semitropical climate, with conditions often favorable for afternoon thunderstorms. When the pressure distribution is altered to bring westerly or northerly winds, periods of hotter and drier weather interrupt the prevailing moist conditions. The high humidity combined with hot days and nights in the interior from May to September produces discomfort at times. The principal relief is by thunderstorms, sometimes accompanied by locally violent and destructive winds.

16. In the colder season the State is alternately subjected to warm tropical air and cold continental air, in periods of varying lengths. However, cold spells seldom last over 3 or 4 days. The ground rarely freezes and then mostly only in the extreme north and only a few inches deep. Although slowly warmed by its southward journey, the cold air occasionally brings large and rather sudden drops in temperature. In winter the Atlantic High is sometimes located far enough west to serve as a barrier to cold air approaching the State. Most frequently this produces a pattern of warm clear weather over the southern part of the State with cold, rainy weather north of the "front," but occasionally the entire State will be under the influence of this subtropical anticyclone.

17. Mean annual precipitation ranges from about 50 in. in the northwest to 65 in. in the southeast. During the freeze-free season, rainfall ranges from 23-25 in. in the Delta to 36-38 in. in the southeast.

18. During the winter the precipitation maximum is centered over the northern and western counties (16-18 in.) with the minimum (13 in.) on the coast. In summer the maximum shifts to the coastal counties (19-21 in.) and the minimum to the Delta counties (9-11 in.). The spring and fall patterns are very similar to the summer pattern. The fall months are the driest of the year, precipitation from about 8-13 in.

Climatic Data Summary

Reporting Station: Hattiesburg (22-3887-09)

Mean Monthly Temperature and Normal
Monthly Precipitation for Period 1941-70:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature, °F	49.9	52.9	58.5	67.1	73.6	79.7	81.4	80.9	76.3	66.5	56.8	51.2	66.2
Precipitation, in.	4.71	5.71	6.96	5.03	4.91	4.26	5.73	5.14	4.24	2.53	4.00	6.07	59.29

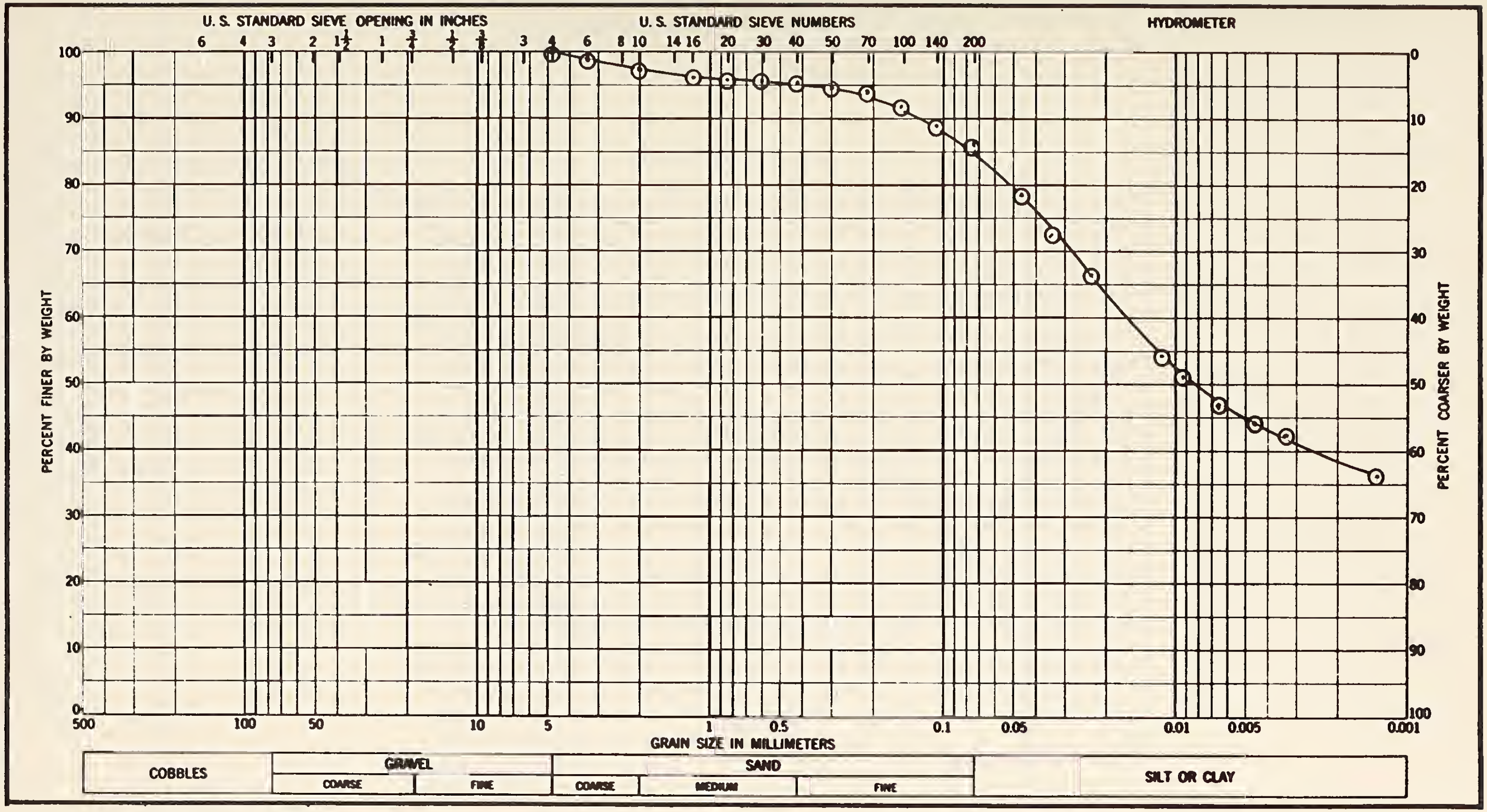
Average Monthly Temperature and
Total Monthly Precipitation for 1971-75:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1971													
Temperature, °F	49.5	50.2	55.8	64.5	69.0	79.9	81.5	80.2	76.9	69.6	54.9	58.1	65.8
Precipitation, in.	2.27	5.47	9.31	1.80	3.81	3.73	3.05	2.49	5.35	0.29	3.87	74.26	55.7
1972													
Temperature,	52.4	52.5	57.0	65.2	70.4	79.1	79.6	82.3	81.0	67.1	54.3	50.4	65.9
Precipitation, in.	8.28	2.03	6.89	0.60	8.32	3.89	3.42	1.58	0.90	4.51	6.47	9.14	56.03
1973													
Temperature, °F	45.6	49.1	62.1	63.6	70.9	79.1	82.1	78.7	77.4	69.3	61.5	48.4	65.7
Precipitation, in.	3.68	2.84	11.35	10.00	5.35	4.12	4.33	5.89	6.69	3.00	5.24	8.95	70.94
1974													
Temperature, °F	58.2	49.9	62.4	64.0	73.9	76.3	80.6	80.0	73.8	63.2	56.4	50.7	65.8
Precipitation, in.	8.45	5.29	7.64	8.21	6.21	3.93	3.36	4.48	6.30	3.38	6.27	3.08	66.60
1975													
Temperature, °F	52.9	55.6	58.3	64.0	73.7	78.5	80.5	80.2	73.0	66.4	56.8	48.1	65.7
Precipitation, in.	8.90	3.21	8.88	7.48	9.68	10.45	5.06	4.91	4.10	6.84	1.78	4.30	75.59

Thornthwaite Moisture Index:

1970	1971	1972	1973	1974	1975
44.09	84.24	58.63	93.74	79.69	93.44

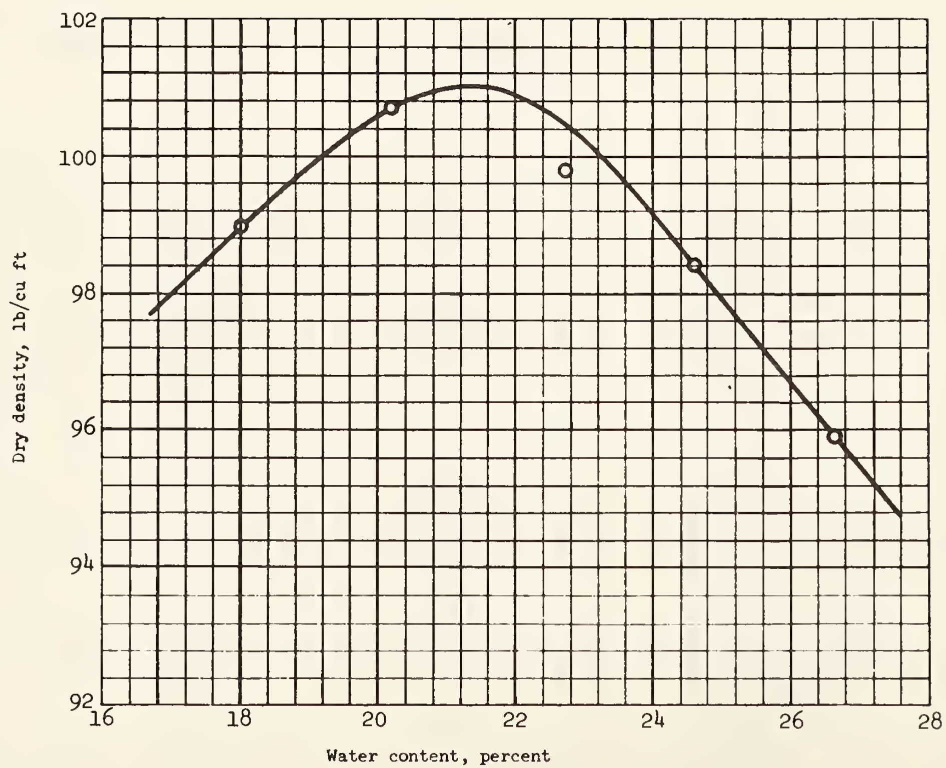
Avg = 75.64



GRADATION CURVE

SITE Hattiesburg, Miss. BORING U-2

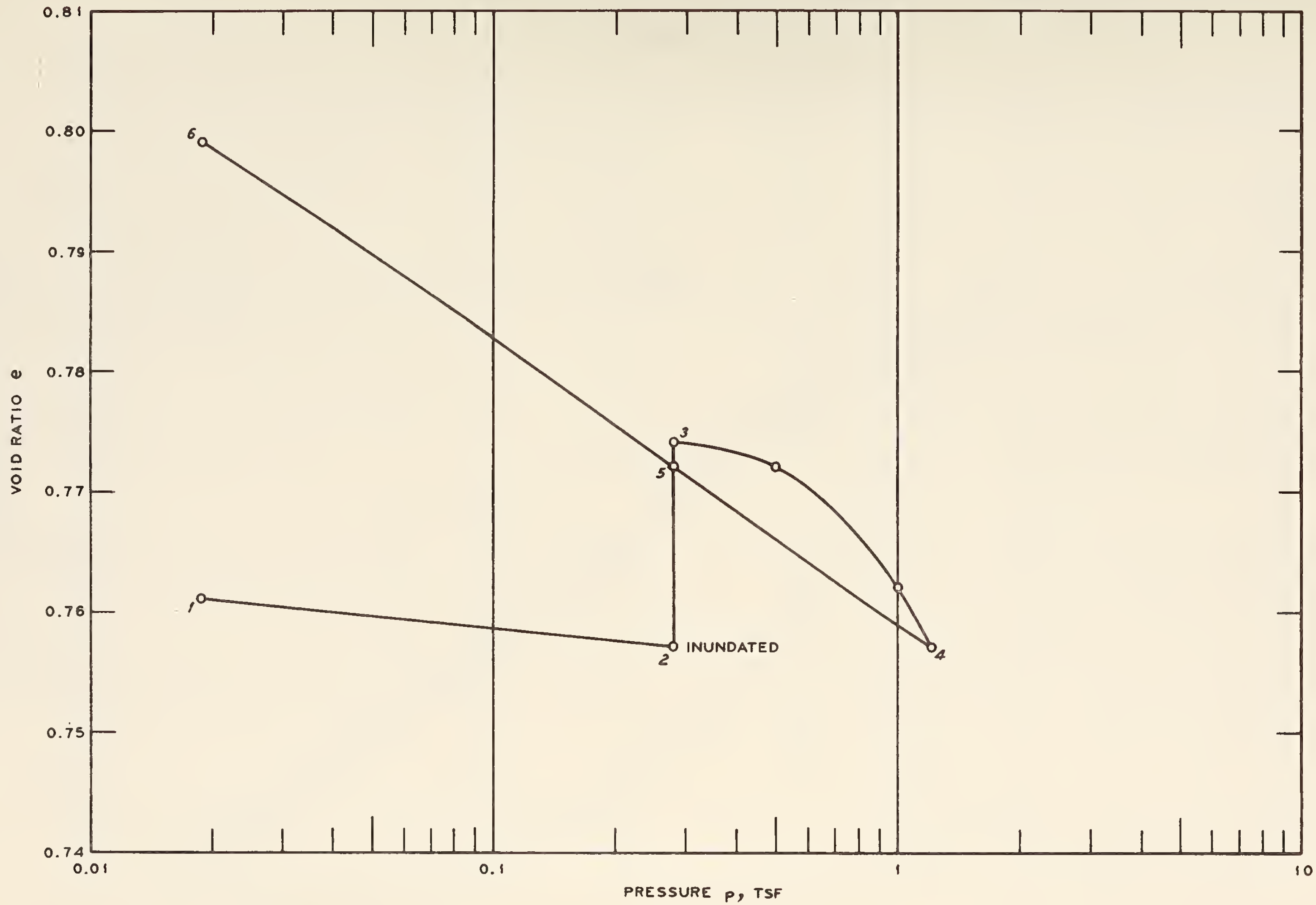
SAMPLE No. 1 DEPTH 1.0-2.9 ft



COMPACTION CURVE

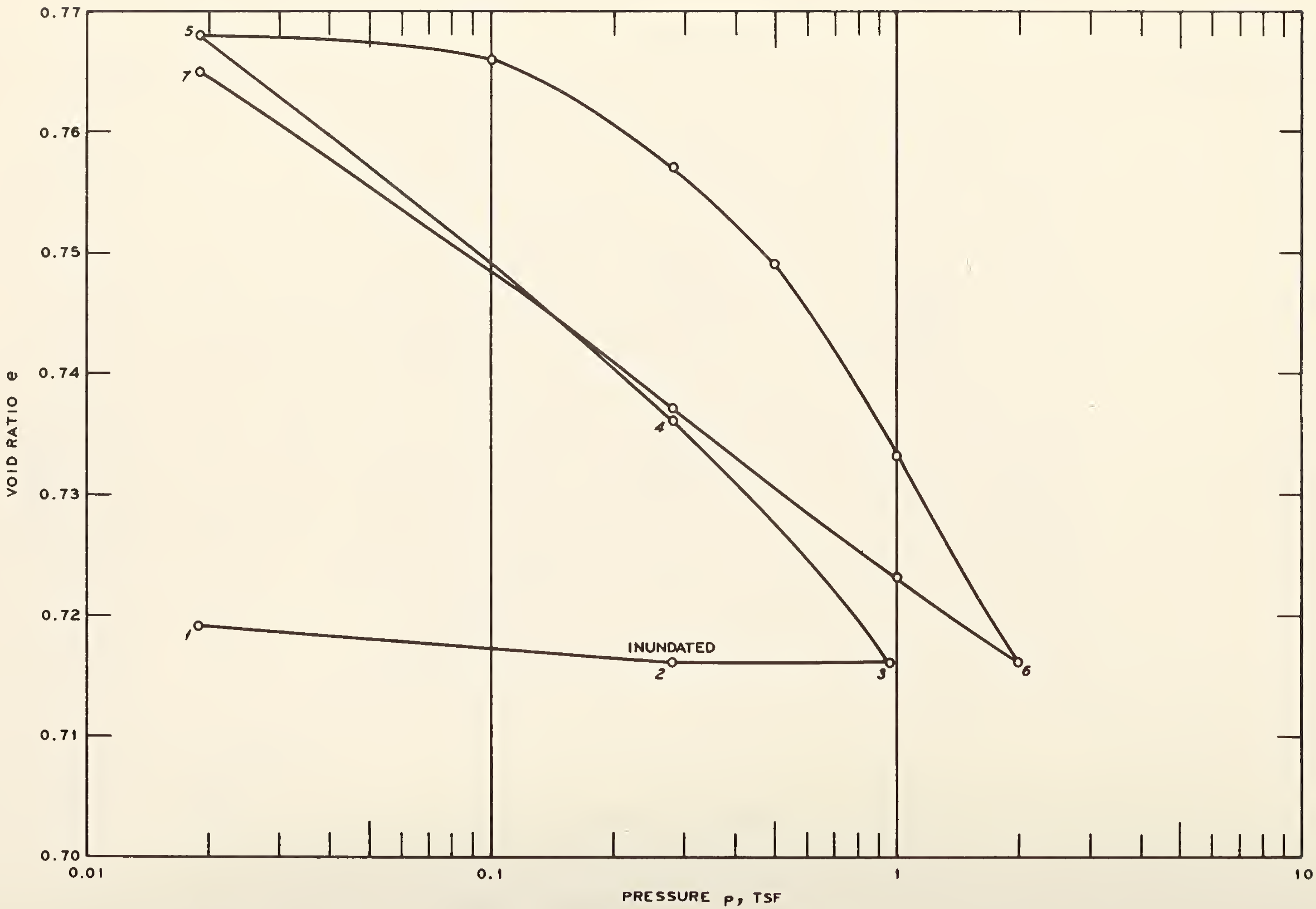
SITE Hattiesburg, Miss.

SAMPLE Disturbed



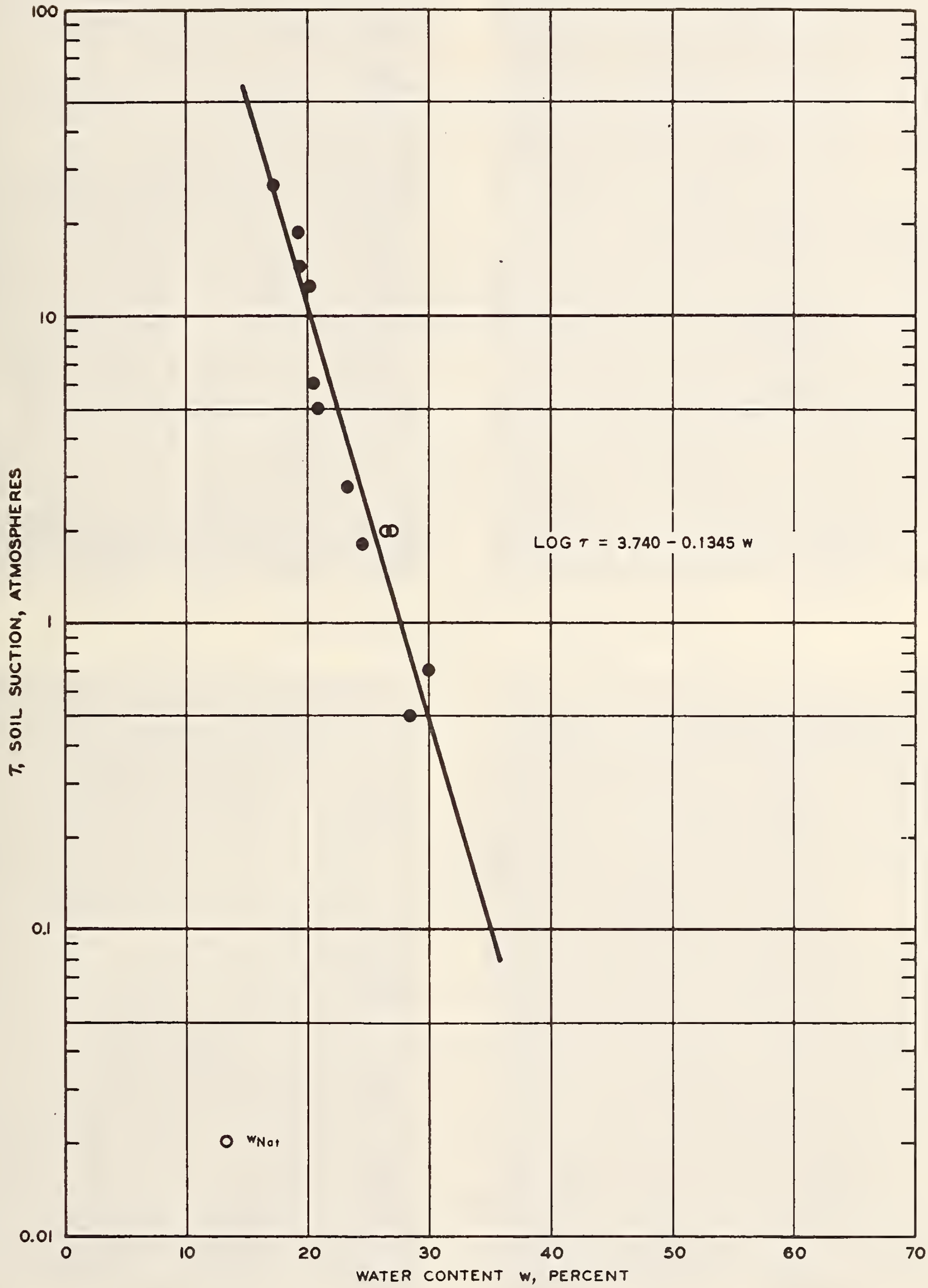
OVERBURDEN SWELL TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

SITE Hattiesburg, Miss. BORING U-2 SAMPLE No. 1 DEPTH 1.0-2.9 ft



CONSTANT VOLUME SWELL PRESSURE TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

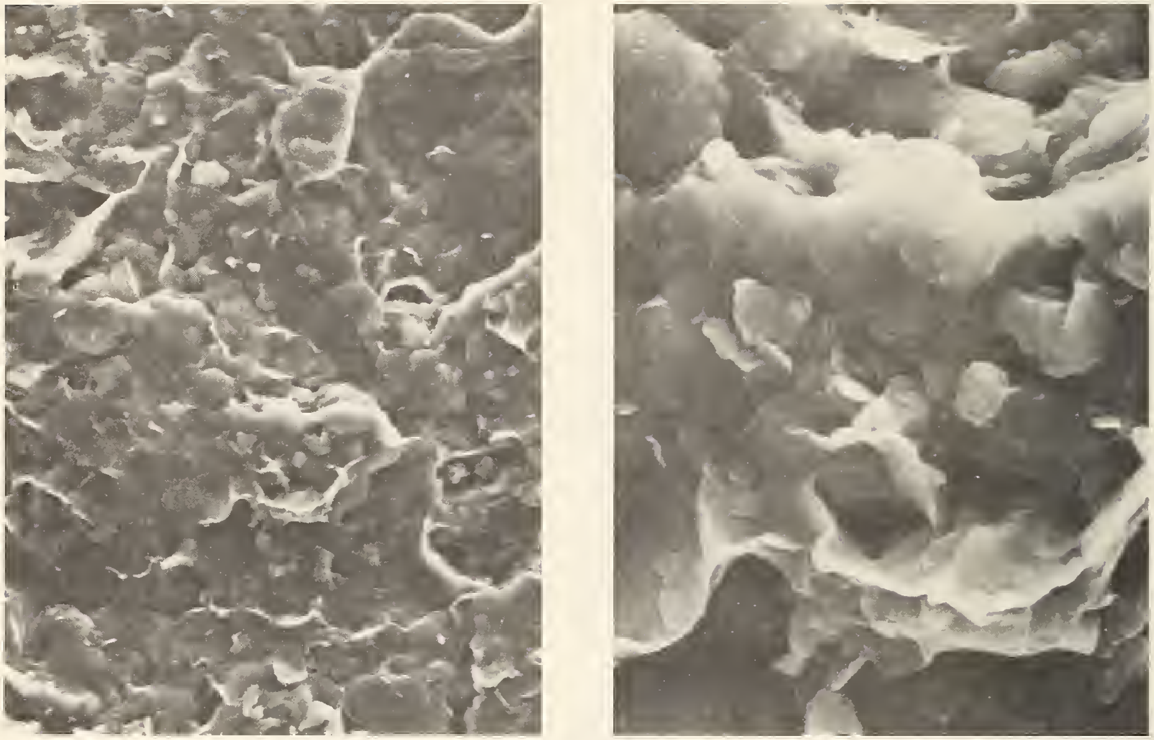
SITE Hattiesburg, Miss. BORING U-2 SAMPLE No. 1 DEPTH 1.0-2.9 ft



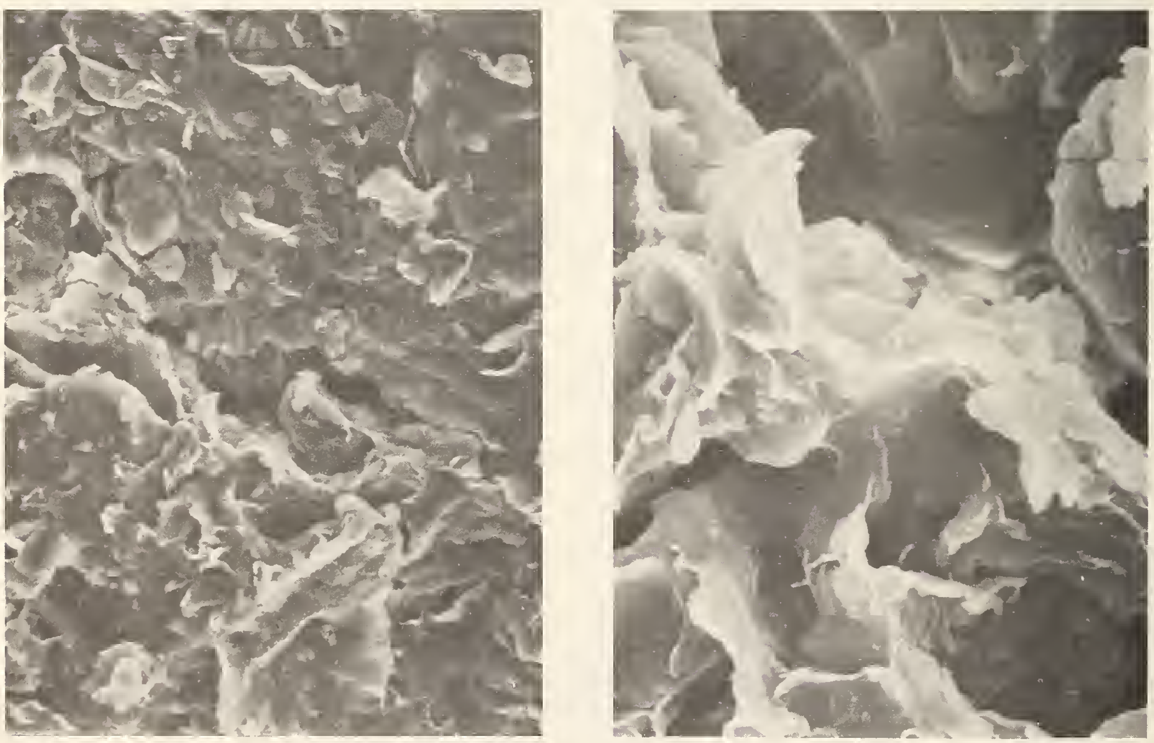
SOIL SUCTION VERSUS WATER CONTENT

SITE Hattiesburg, Miss. BORING U-2

SAMPLE No. 1 DEPTH 1.0-2.9 ft



a. Normal to Y, ×650 and ×2300



10 μm

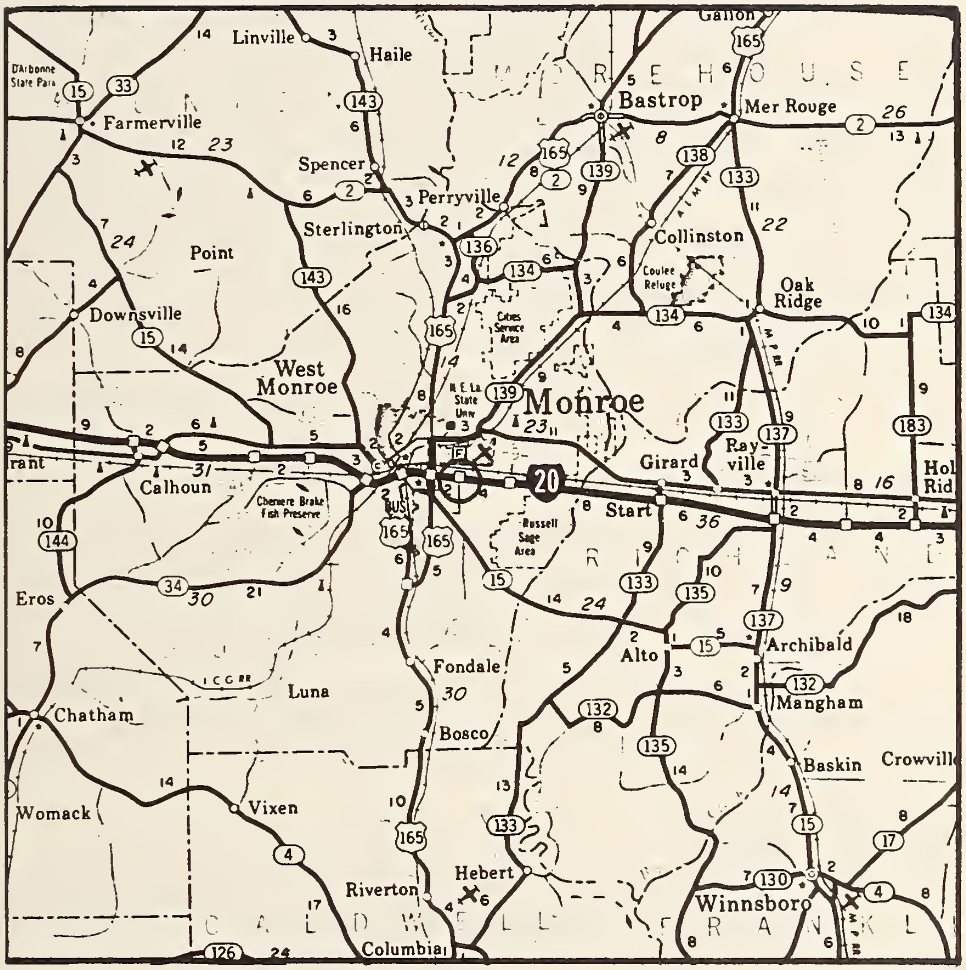
b. Normal to X, ×650 and ×2300

10 μm

SITE Hattiesburg, Miss. BORING U-2

SAMPLE No. 1 DEPTH 1.0-2.9 ft

SAMPLING SITE NO. 3, MONROE, LA.



Site Location Information

19. Sampling site No. 3 is located in north-central Louisiana near the eastern boundary of Monroe, La. The site is located approximately 1000 ft South of I-20 and Milhaven Road junction on Milhaven Road (Milhaven Road crosses I-20 approximately 3.5 miles east of I-20 and U. S. 165 junction). Samples were taken in east right-of-way of Milhaven Road (approximately 38 ft east of centerline).

Site Description

20. Sampling site is located at grade in flat terrain. Drainage is in a southerly direction on a very slight slope. Surrounding area

has a complete grass cover and partial tree cover.

Site Geology

21. Sampling site is located in the Mississippi Alluvial Plain Section of the Coastal Plain Physiographic Province. The topography is essentially flat. The materials consist of alluvial deposits of Holocene sands, silts, and clays associated with earlier courses of the Mississippi River. The samples were taken in an alluvial deposit called backswamp which consists of dark colored organic silty clays or clays which are deposited beyond the former river channel during flood stage. The backswamp deposits are among the most fine-grained materials in this area and the most likely to pose problems with respect to volume change.

Sample Description

22. The alluvial materials sampled are stiff, nonindurated, unweathered, noncalcareous moderate brown (5 YR 3/4) clay with a slight organic (earthy) odor. Samples exhibit fractures and voids. Organic detritus and iron-oxide staining are common. The SEM photographs indicate moderate development of particle orientation with some wavy stratification.

Description of Climate

23. The principal influences that determine the climate of Louisiana are its subtropical latitude and its proximity to the Gulf of Mexico. The marine tropical influence is evident from the fact that the average water temperatures of the Gulf along the Louisiana shore range from 64°F in February to 84°F in August. Elevation and type of soil are factors of varying importance.

24. In summer the prevailing southerly winds provide most semitropical weather often favorable for afternoon thundershowers. When westerly to northerly winds occur, periods of hotter and drier weather interrupt the prevailing moist condition. In the colder season the State is subjected alternately to tropical air and cold continental air, in periods of varying length. Although warmed by its southward journey, the cold air occasionally brings large and rather sudden drops in temperature, but conditions are usually less severe than farther west.

25. Louisiana is south of the usual track of winter storm centers, but occasionally one moves this far south. In some winters a succession of such centers will develop in the Gulf of Mexico and move over or near the State. The winter of 1957-58 was a classic example. The State is occasionally in the path of tropical storms or hurricanes.

26. From December to May the water of the Mississippi River is usually colder than the air temperature, which favors river fogs during this season, particularly with weak southerly winds. In the more southern sections, lakes also serve to modify the extremes of temperature and to increase fogginess over narrow stripes along the shores.

27. Mean annual precipitation ranges from 46 in. in Caddo Parish to as much as 66 in. in parts of St. Mary, Assumption, Terrebonne, and Lafourche Parishes. A median line of 56 in. per year runs from Hackberry northward to Leesville, Montgomery, Winona, Luna, and southward to Harrisonburg and Deerpark on the Mississippi River. This line separates areas of lower precipitation averages to the north from areas of higher precipitation to the south.

28. During the summer months, seasonal rainfall usually increases from the northwest (9 in.) toward the southeast (22 in.). In the winter this pattern is reversed with the heaviest seasonal precipitation (17 in.) in the area extending from the Carroll Parishes southwestward to Winn and southward to St. Landry, with the least (13 in.) in the lower Delta. During the summer months the rich source of moist tropical air results in almost daily showers in the coastal parishes; however, shower frequency diminishes with distance from the Gulf coast toward the northern parishes. In the winter months the northern portion of the State is invaded by cold air which tends to stall and become stationary. This sometimes produces prolonged rains over that area, while clear weather continues in the southern parishes. The pattern of spring rains is similar to that of winter, while fall rains are distributed in the same manner as summer rains. However, fall (September, October, and November) is the driest season of the year, with precipitation ranging from 9 in. in the north to 15 in. in the southeast. Spring precipitation ranges from 13 in. on the coast to 18 in. in the central interior.

29. The average annual temperature ranges from 66°F in northern divisions to 69°F in southern divisions. The lowest January average is 49°F in the northwest and north-central ranging upward to 57°F in the southeast. The highest July average is 83°F in the northwest and north-central, ranging downward to 81°F in the east-central (north of Lake Pontchartrain). This reversal of temperature distribution with warmer summers in the northern portion than in the southern portion, is due to the almost daily showers in the parishes near or on the Gulf of Mexico.

Climatic Data Summary

Reporting Station: Monroe FAA Airport (16-6303-02)

Mean Monthly Temperature and Normal
Monthly Precipitation for Period 1941-70:

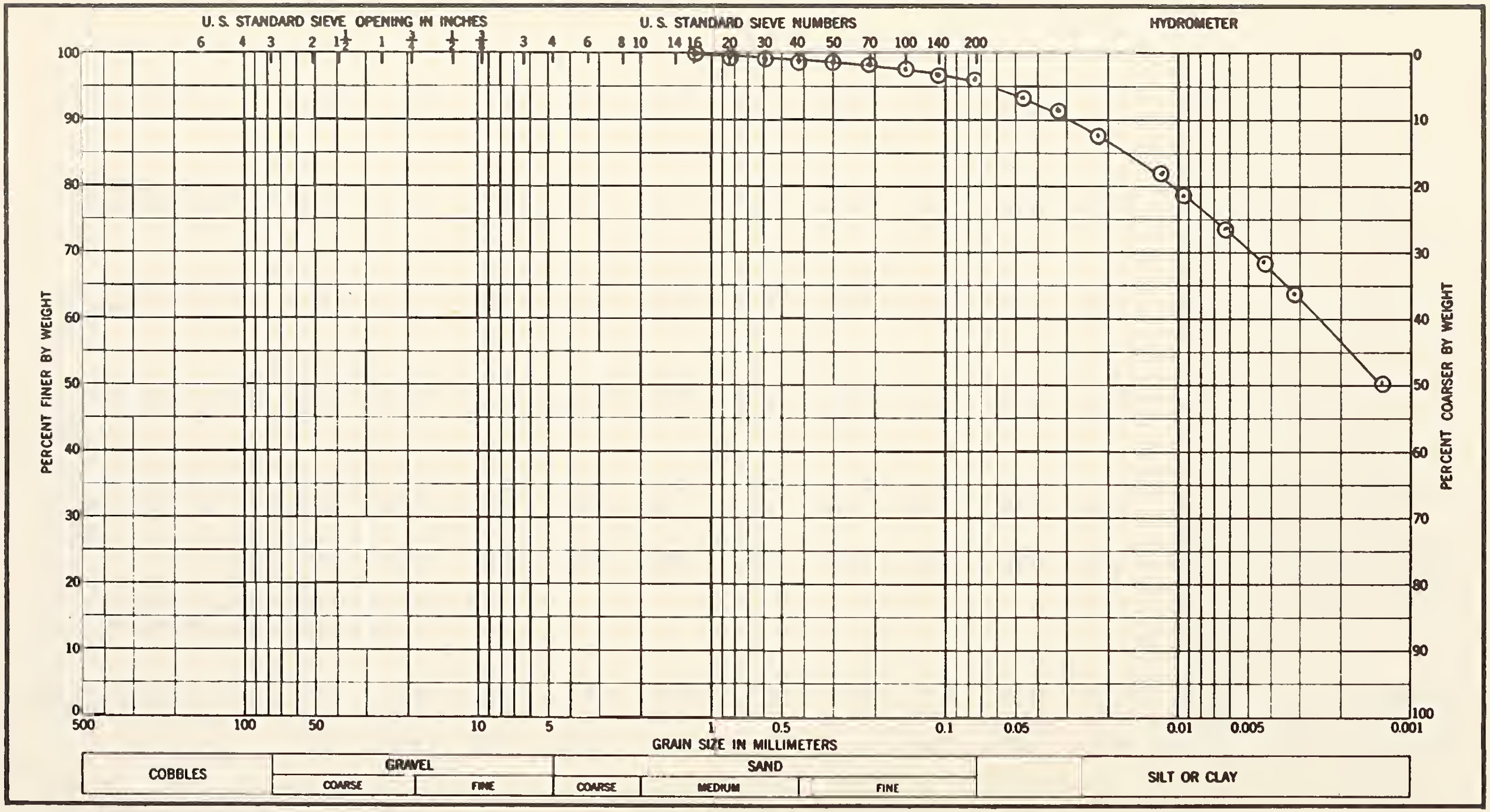
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature, °F	46.7	49.8	56.1	65.9	73.3	80.1	82.3	81.7	75.9	65.8	55.0	48.3	65.1
Precipitation, in.	4.61	4.83	4.89	5.20	4.79	3.81	4.66	2.42	2.81	2.56	4.24	4.80	49.62

Average Monthly Temperature and
Total Monthly Precipitation for 1971-75:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1971													
Temperature, °F	47.4	48.9	52.9	63.5	69.7	81.6	80.4	79.4	76.2	69.8	54.4	54.9	64.9
Precipitation, in.	2.23	5.43	2.68	3.35	7.20	3.75	6.15	1.56	2.09	0.37	3.04	7.48	45.33
1972													
Temperature, °F	49.9	51.2	58.6	67.4	73.5	79.7	79.6	81.6	80.0	66.0	50.4	46.2	65.3
Precipitation, in.	9.27	2.77	5.72	2.06	2.32	5.34	3.45	2.29	4.16	3.97	3.63	6.18	51.16
1973													
Temperature, °F	43.3	47.2	60.8	60.4	69.8	80.2	83.0	78.8	77.4	69.9	60.9	46.5	64.9
Precipitation, in.	5.91	2.13	8.80	5.15	4.84	1.31	3.59	1.18	5.25	7.20	4.87	5.74	55.97
1974													
Temperature, °F	49.0	51.2	63.9	65.3	76.1	77.5	83.1	79.6	69.9	64.0	54.4	48.3	65.2
Precipitation, in.	11.94	4.11	4.33	8.27	5.18	4.51	3.28	6.16	4.50	2.92	4.25	7.43	66.88
1975													
Temperature, °F	50.2	50.0	55.2	63.6	73.7	79.0	81.5	80.4	71.4	65.3	55.4	46.2	64.3
Precipitation, in.	4.40	6.36	7.99	4.19	8.56	6.13	10.80	4.07	1.87	5.41	1.84	0.81	62.43

Thornthwaite Moisture Index:

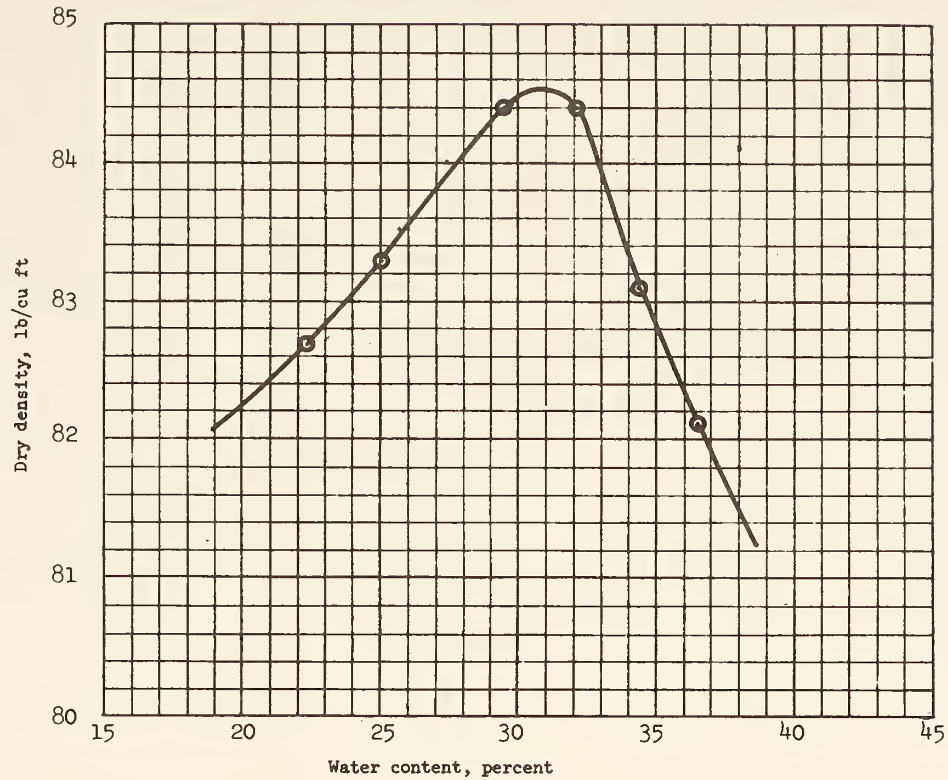
1970	1971	1972	1973	1974	1975	
31.98	33.89	55.65	79.42	101.56	88.24	Avg = 65.12



GRADATION CURVE

SITE Monroe, La. BORING U-1

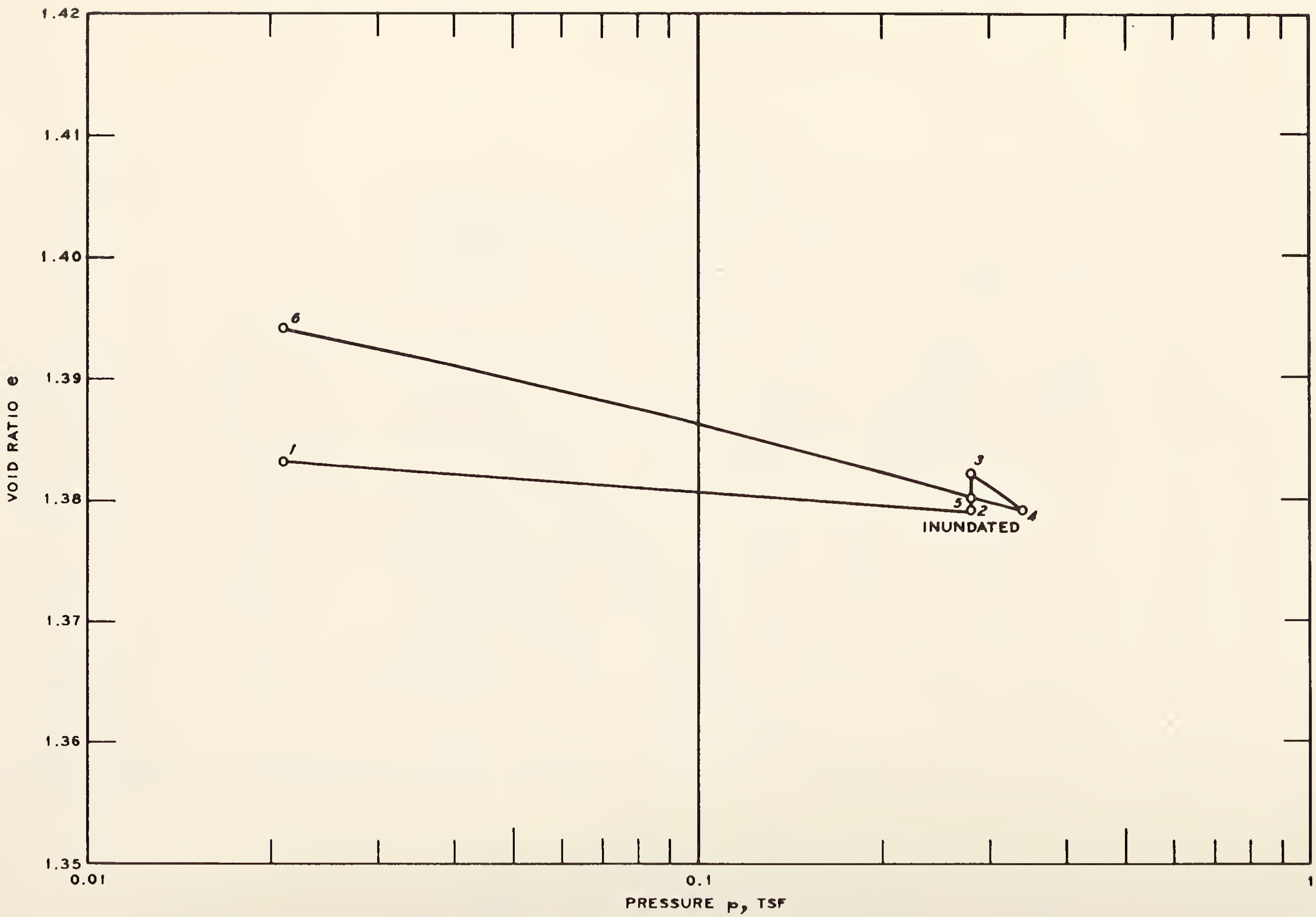
SAMPLE No. 1 DEPTH 1.0-2.8 ft



COMPACTION CURVE

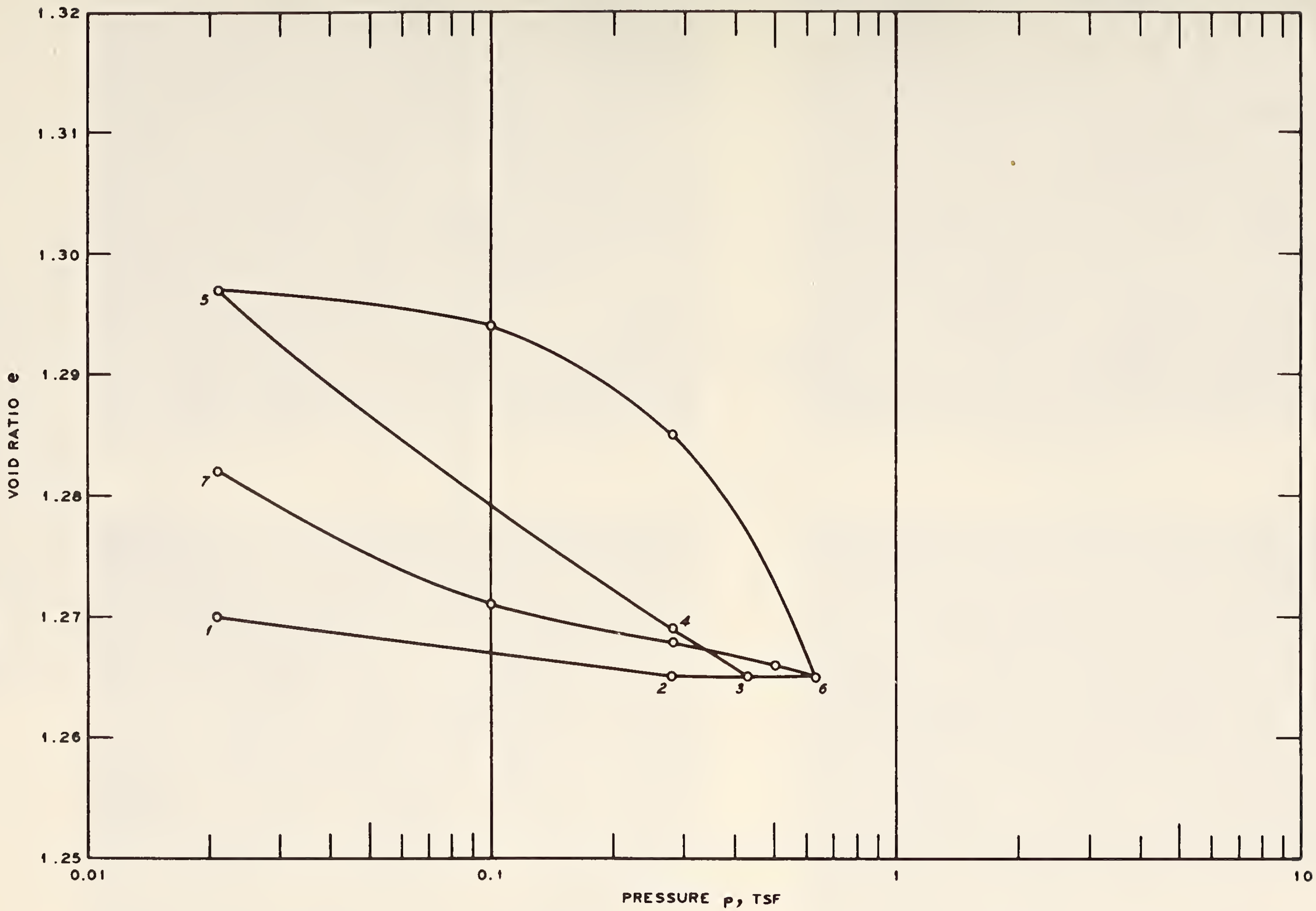
SITE Monroe La.

SAMPLE Disturbed



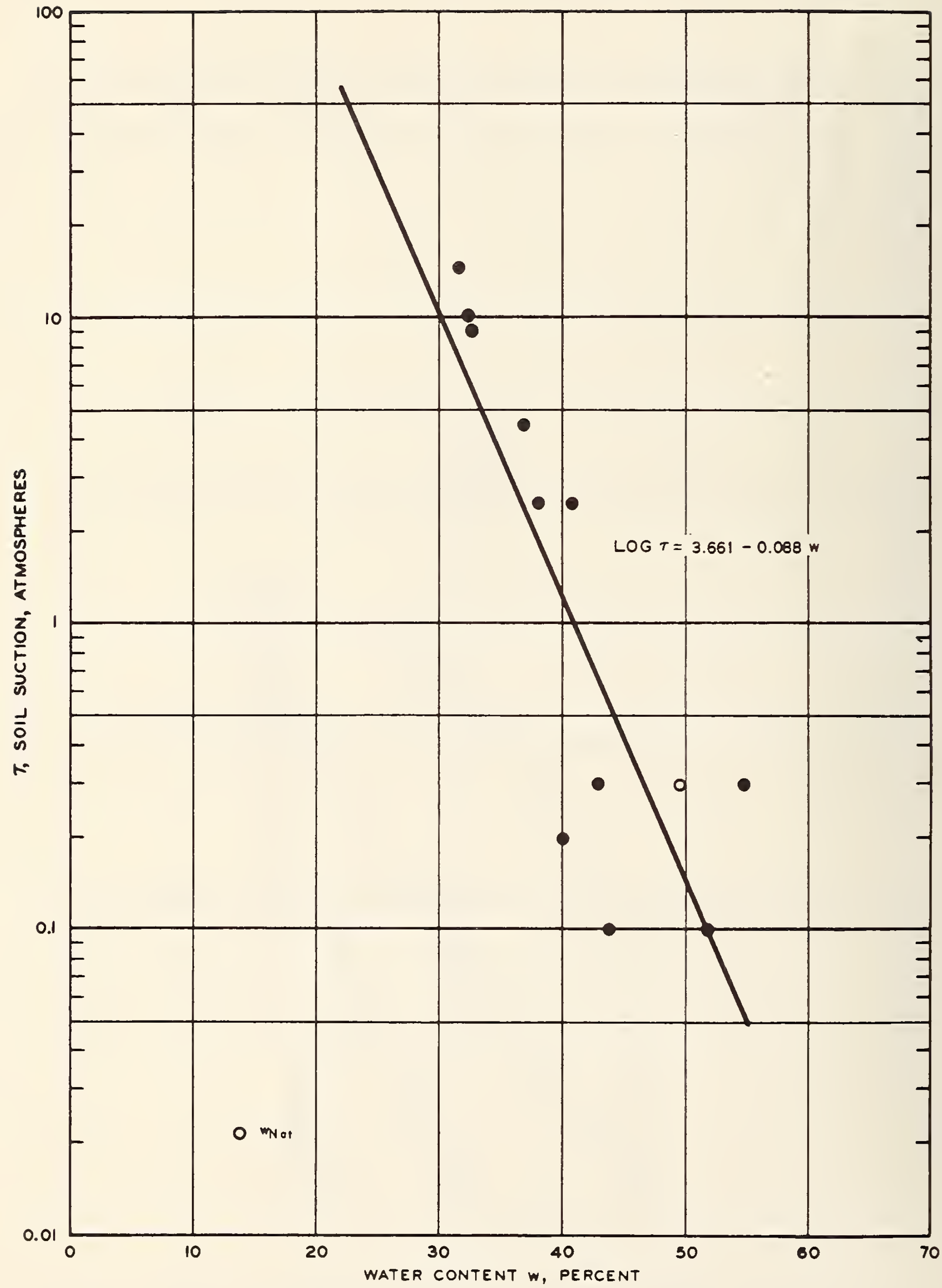
OVERBURDEN SWELL TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

SITE Monroe, La. BORING U-1 SAMPLE No. 1 DEPTH 1.0-2.8 ft



CONSTANT VOLUME SWELL PRESSURE TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

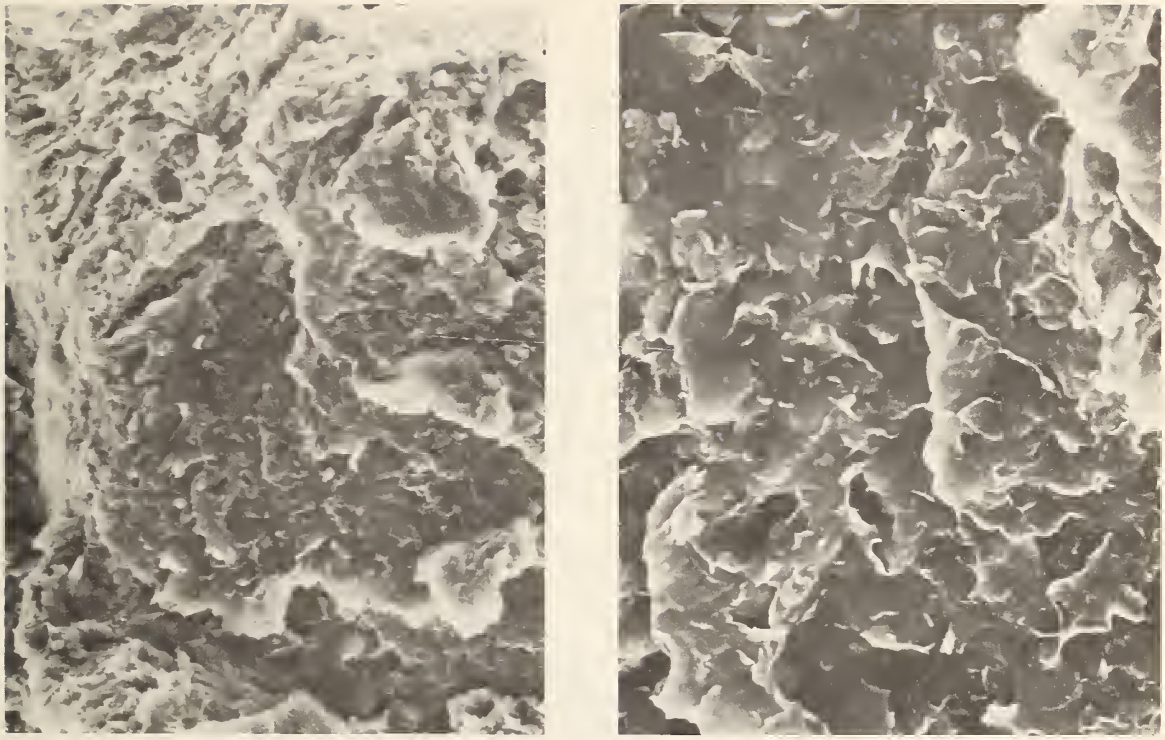
SITE Monroe, La. BORING U-1 SAMPLE No. 1 DEPTH 1.0-2.8 ft



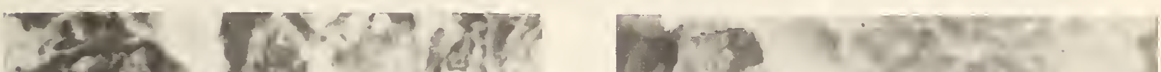
SOIL SUCTION VERSUS WATER CONTENT

SITE Monroe, La. BORING U-1

SAMPLE No. 1 DEPTH 1.0-2.8 ft



a. Normal to Y, ×650 and ×2300



10 μm

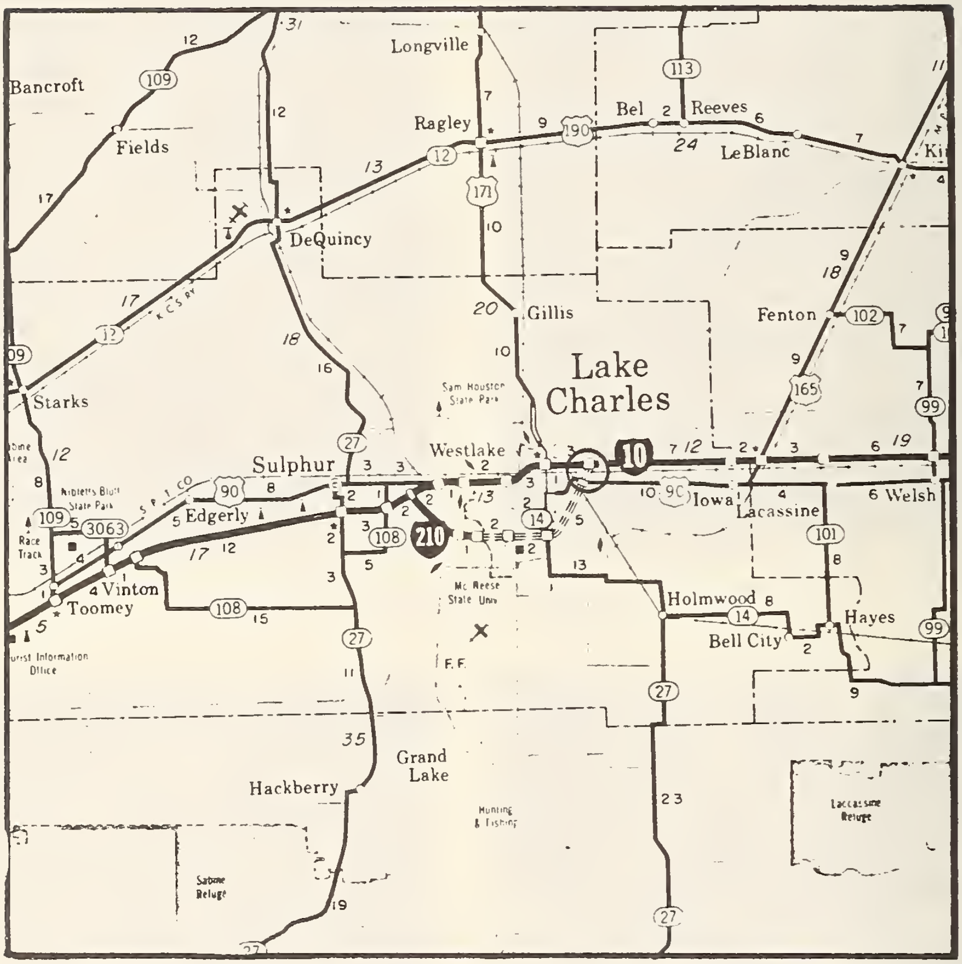
b. Normal to X, ×650 and ×2300

10 μm

SITE Monroe, La. BORING U-1

SAMPLE No. 1 DEPTH 1.0-2.8 ft

SAMPLING SITE NO. 4, LAKE CHARLES, LA.



Site Location Information

30. Sampling site No. 4 is located in southeastern Louisiana near the eastern boundary of Lake Charles, La. The site is located approximately 1500 ft south of I-10 at milepost 38. Milepost 38 is just west of the I-10 and I-210 eastern junction. Samples were taken on private property near one of the borrow pits to be used for embankment construction.

Site Description

31. Sampling site is located at grade in flat terrain. Drainage is in a southerly direction on a very slight slope. Surrounding area

has a complete grass cover and no trees.

Site Geology

32. Sampling site is located in the West Gulf Coastal Plain Section of the Coastal Plain Physiographic Province. The area has essentially flat topography. The materials consist of Pleistocene and older alluvial deposits or terraces associated with streams flowing into the Gulf of Mexico. Samples were taken from the Prarie Terrace which is the youngest of the four recognizeable terraces in the area. The Prarie Terrace consists of interbedded dark silty clays and sand lenses. The Prarie Terrace of Louisiana and Mississippi correlates approximately with the Beaumont Terrace of east Texas.

Sample Description

33. The Prarie Terrace material sampled is a hard, nonindurated, weathered, mottled dark yellowish orange (10 YR 6/6) to medium gray (N5) silty clay. The material is generally noncalcareous except in highly weathered samples. Undulatory stratifications are present and open cracks occur along these surfaces. The SEM photographs indicate a random particle orientation with considerable voids.

Description of Climate

34. The principal influences that determine the climate of Louisiana are its subtropical latitude and its proximity to the Gulf of Mexico. The marine tropical influence is evident from the fact that the average water temperatures of the Gulf along the Louisiana shore range from 64°F in February to 84°F in August. Elevation and type of soil are factors of varying importance.

35. In summer the prevailing southerly winds provide most semitropical weather often favorable for afternoon thundershowers. When westerly to northerly winds occur, periods of hotter and drier weather interrupt the prevailing moist condition. In the colder season the State is subjected alternately to tropical air and cold continental air, in periods of varying length. Although warmed by its southward journey, the cold air occasionally brings large and rather sudden drops in temperature, but conditions are usually less severe than farther west.

36. Louisiana is south of the usual track of winter storm centers,

but occasionally one moves this far south. In some winters a succession of such centers will develop in the Gulf of Mexico and move over or near the State. The winter of 1957-58 was a classic example. The State is occasionally in the path of tropical storms or hurricanes.

37. From December to May the water of the Mississippi River is usually colder than the air temperature, which favors river fogs during this season, particularly with weak southerly winds. In the more southern sections, lakes also serve to modify the extremes of temperature and to increase fogginess over narrow stripes along the shores.

38. Mean annual precipitation ranges from 46 in. in Caddo Parish to as much as 66 in. in parts of St. Mary, Assumption, Terrebonne, and Lafourche Parishes. A median line of 56 in. per year runs from Hackberry northward to Leesville, Montgomery, Winona, Luna, and southward to Harrisonburg and Deerpark on the Mississippi River. This line separates areas of lower precipitation averages to the north from areas of higher precipitation to the south.

39. During the summer months, seasonal rainfall usually increases from the northwest (9 in.) toward the southeast (22 in.). In the winter this pattern is reversed with the heaviest seasonal precipitation (17 in.) in the area extending from the Carroll Parishes southwestward to Winn and southward to St. Landry, with the least (13 in.) in the lower Delta. During the summer months the rich source of moist tropical air results in almost daily showers in the coastal parishes; however, shower frequency diminishes with distance from the Gulf coast toward the northern parishes. In the winter months the northern portion of the State is invaded by cold air which tends to stall and become stationary. This sometimes produces prolonged rains over that area, while clear weather continues in the southern parishes. The pattern of spring rains is similar to that of winter, while fall rains are distributed in the same manner as summer rains. However, fall (September, October, and November) is the driest season of the year, with precipitation ranging from 9 in. in the north to 15 in. in the southeast. Spring precipitation ranges from 13 in. on the coast to 18 in. in the central interior.

40. The average annual temperature ranges from 66°F in northern

divisions to 69°F in southern divisions. The lowest January average is 49°F in the northwest and north-central ranging upward to 57°F in the southeast. The highest July average is 83°F in the northwest and north-central, ranging downward to 81°F in the east-central (north of Lake Pontchartrain). This reversal of temperature distribution with warmer summers in the northern portion than in the southern portion, is due to the almost daily showers in the parishes near or on the Gulf of Mexico.

Climatic Data Summary

Reporting Station: Lake Charles Weather Service Office-Airport (16-5078-07)

Mean Monthly Temperature and Normal
Monthly Precipitation for Period 1941-70:

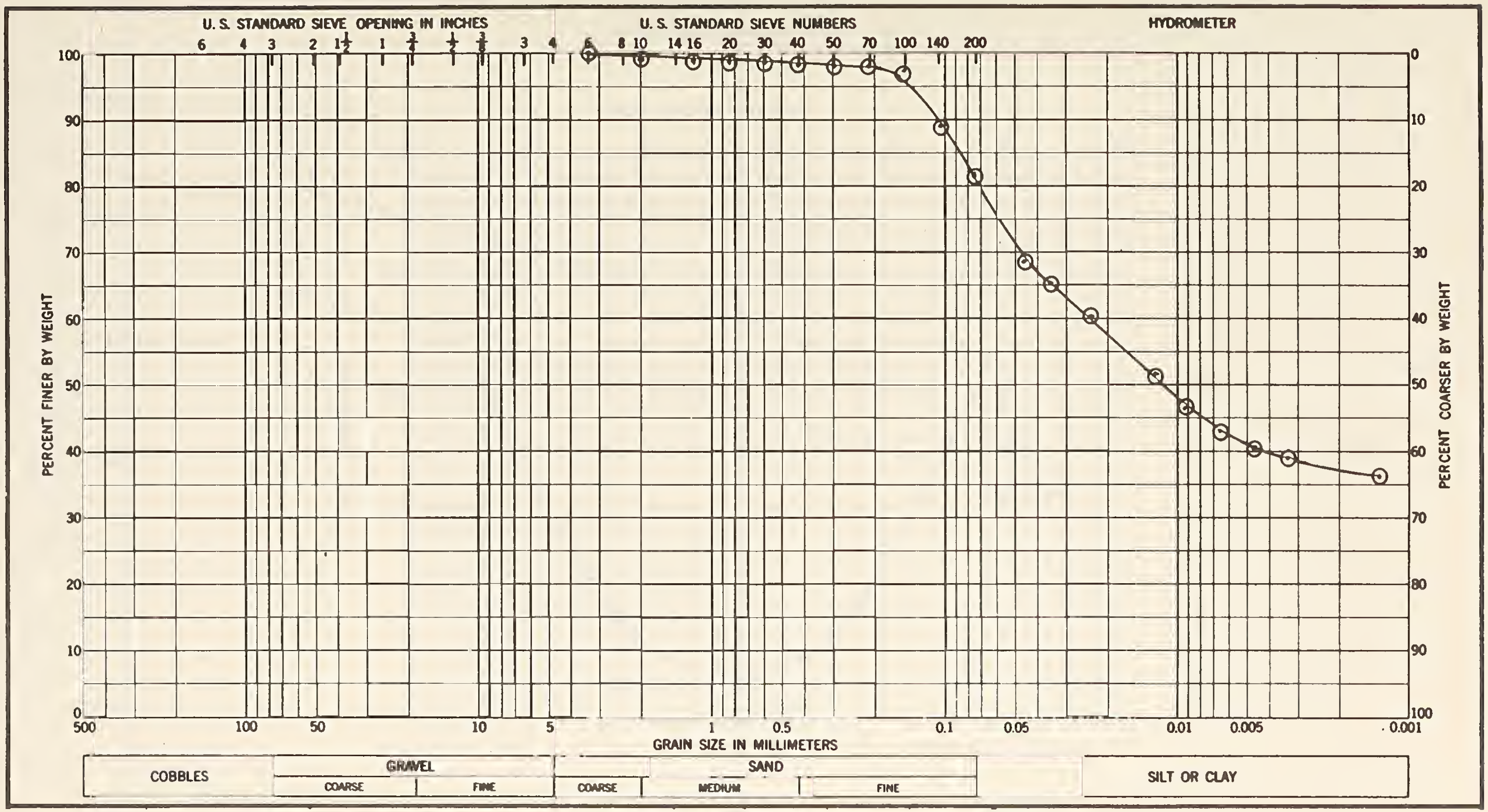
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature, °F	52.3	55.1	60.3	68.9	75.2	80.7	82.4	82.2	78.4	70.0	60.2	54.3	68.3
Precipitation, in.	4.04	4.47	3.84	4.33	5.06	5.04	6.55	4.75	4.13	3.48	4.08	5.70	55.47

Average Monthly Temperature and
Total Monthly Precipitation for 1971-75:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1971													
Temperature, °F	55.6	55.6	59.1	66.5	74.3	82.1	83.0	81.7	80.1	74.8	60.2	61.8	69.6
Precipitation, in.	0.78	3.45	0.27	0.79	5.78	2.23	4.41	6.31	5.38	2.64	1.64	9.90	43.72
1972													
Temperature, °F	55.8	56.3	63.1	69.8	74.1	81.3	80.3	80.9	79.6	69.0	54.7	53.0	68.2
Precipitation, in.	7.73	2.24	2.23	1.58	4.53	0.93	7.75	6.64	5.82	6.44	4.30	5.47	55.66
1973													
Temperature, °F	48.8	51.5	64.4	64.5	72.7	79.9	82.7	79.6	78.7	72.6	66.7	52.4	67.9
Precipitation, in.	4.14	2.94	7.40	10.95	7.48	3.98	2.96	3.29	19.96	4.12	3.01	4.80	75.03
1974													
Temperature, °F	58.0	55.6	66.3	68.2	76.0	78.7	82.0	80.8	75.2	68.9	59.9	54.5	68.7
Precipitation, in.	12.96	3.89	3.37	2.95	11.01	2.89	1.28	5.54	3.60	4.15	7.30	7.77	66.44
1975													
Temperature, °F	56.7	56.9	61.1	66.6	75.8	79.8	81.4	80.9	75.1	69.4	60.3	51.8	68.0
Precipitation, in.	6.06	1.08	2.41	7.22	7.04	5.43	6.96	5.15	5.37	2.50	4.22	2.07	55.51

Thornthwaite Moisture Index:

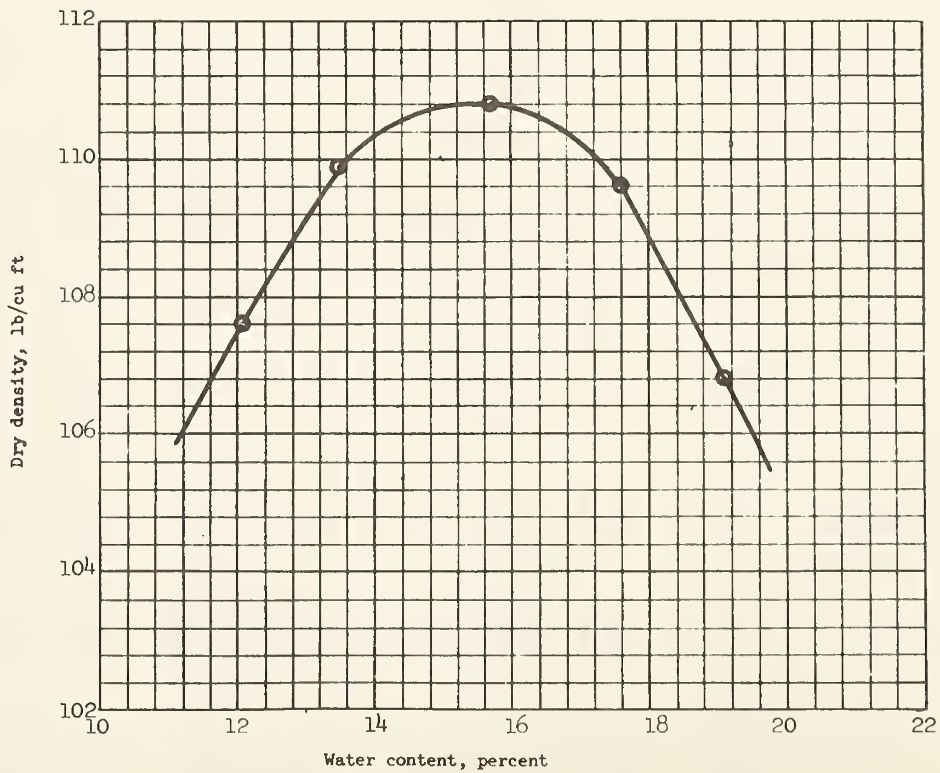
1970	1971	1972	1973	1974	1975	
48.12	34.63	50.11	94.32	63.35	58.51	Avg = 58.17



GRADATION CURVE

SITE Lake Charles, La. BORING U-2

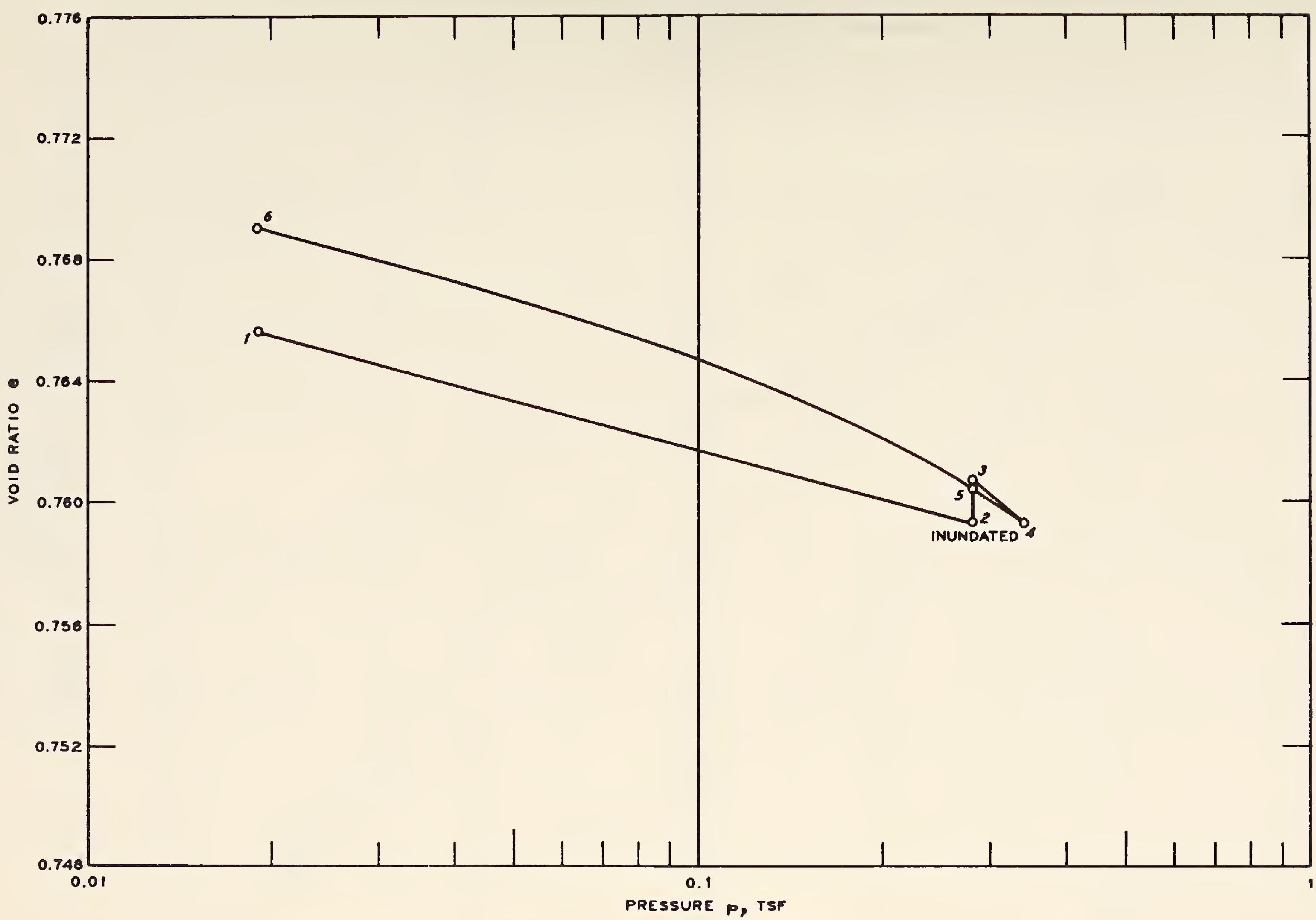
SAMPLE No. 1 DEPTH 1.0-3.1 ft



COMPACTION CURVE

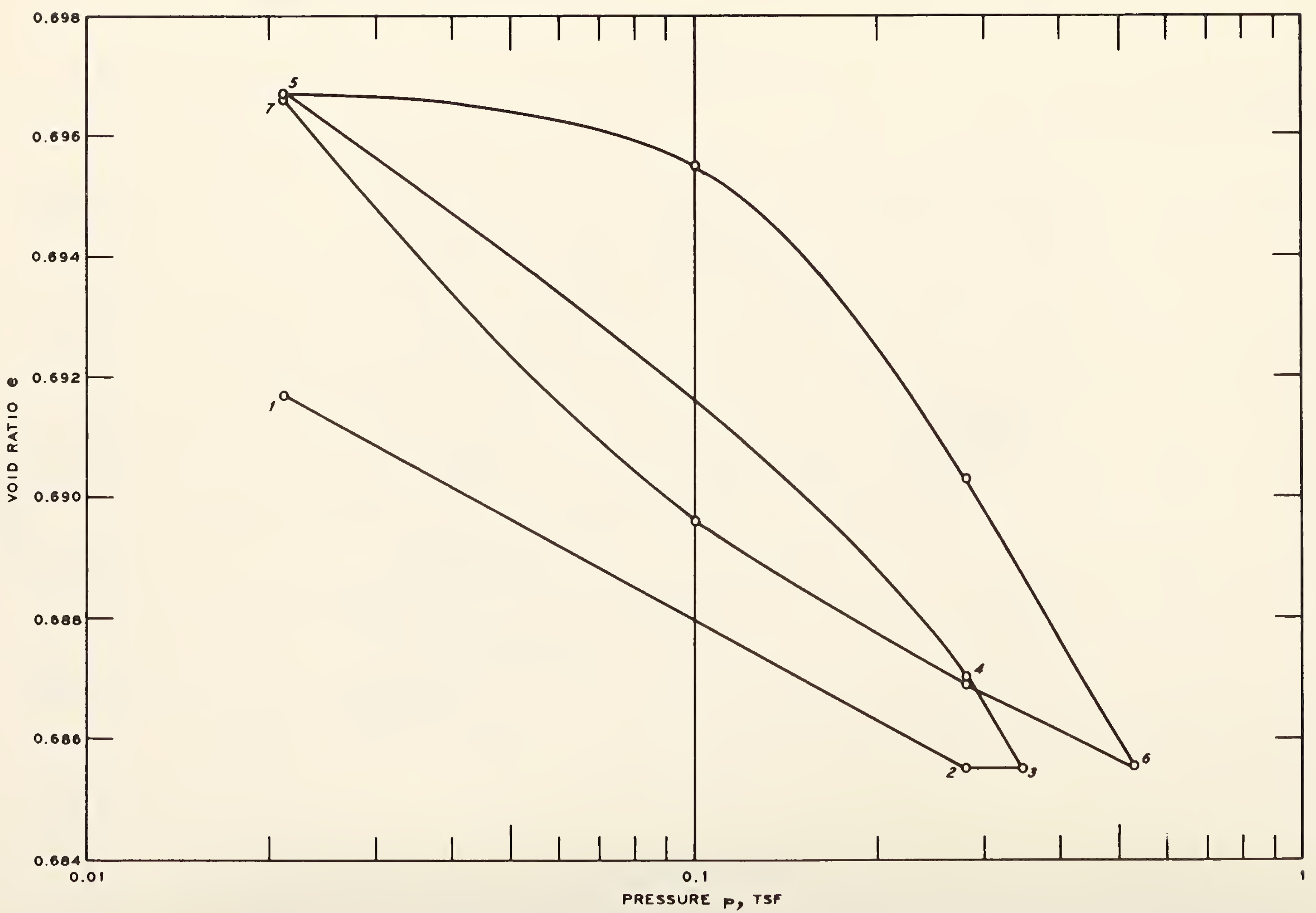
SITE Lake Charles, La.

SAMPLE Disturbed



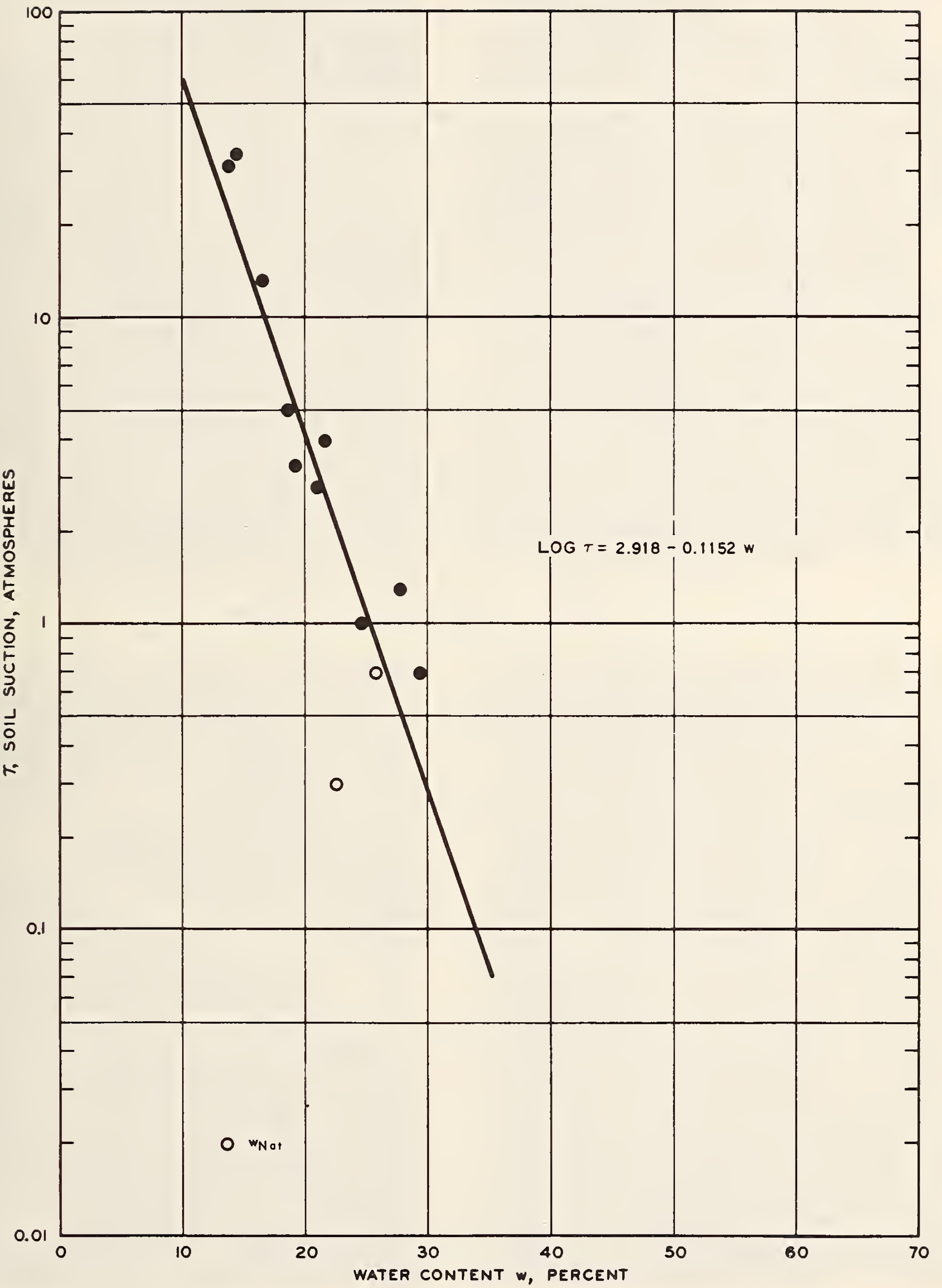
OVERBURDEN SWELL TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

SITE Lake Charles, La. BORING U-2 SAMPLE No. 1 DEPTH 1.0-3.1 ft



CONSTANT VOLUME SWELL PRESSURE TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

SITE Lake Charles, La. BORING U-2 SAMPLE No. 1 DEPTH 1.0-3.1 ft



SOIL SUCTION VERSUS WATER CONTENT

SITE Lake Charles, La. BORING U-2

SAMPLE No. 1 DEPTH 1.0-3.1 ft

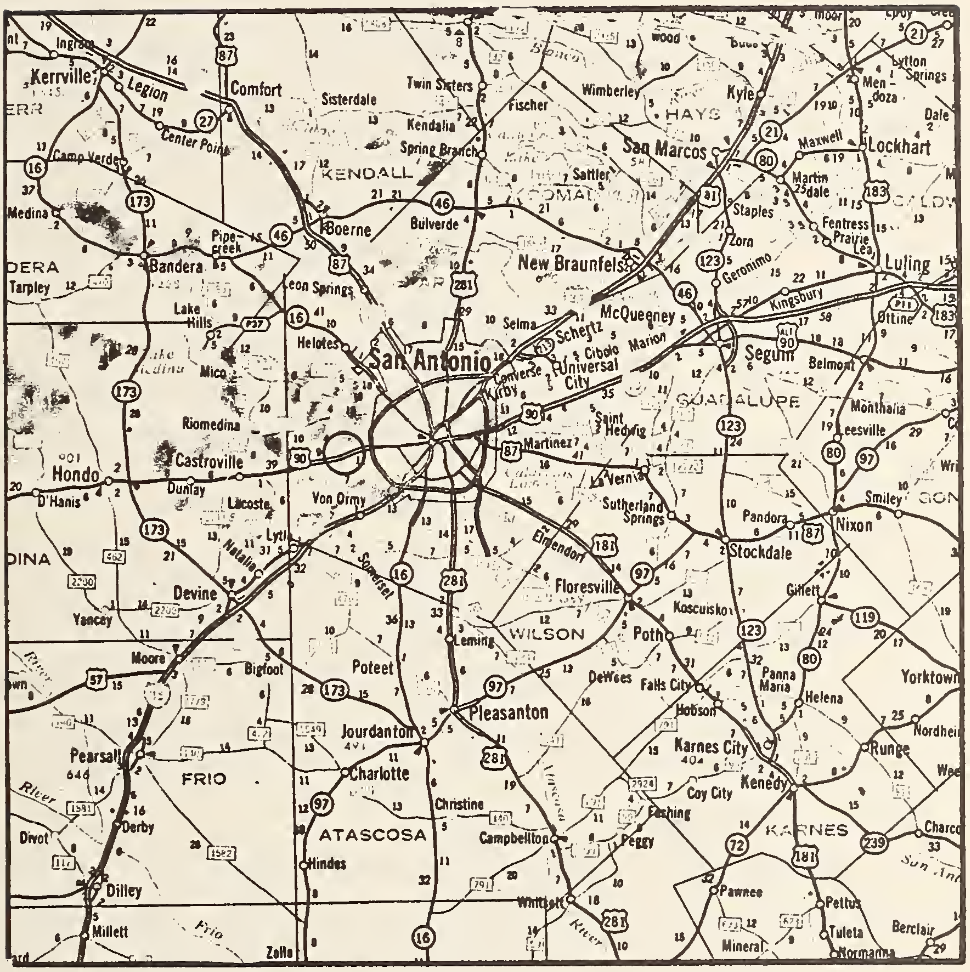
a. Normal to Y, ×650 and ×2300

b. Normal to X, ×650 and ×2300

SITE Lake Charles, La. BORING U-2

SAMPLE No. 1 DEPTH 1.0-3.1 ft

SAMPLING SITE NO. 5, SAN ANTONIO, TEX.



Site Location Information

41. Sampling site No. 5 is located in south-central Texas near the western boundary of San Antonio, Tex. The site is located approximately 1500 ft east of U. S. 90 and FM 1604 junction adjacent to the ponded field test section. Samples were taken in the median of the divided four-lane road at station 241+35 which is 65 ft east of the eastern border of the ponded section.

Site Description

42. Sampling site is located in a cut section (≈ 4 ft at sampling site) in open, rolling terrain. Drainage is in an easterly direction on

a moderate slope. Surrounding area has a complete grass cover and no trees.

Site Geology

43. Sampling site is located in the West Gulf Coastal Plain Section of the Coastal Plain Physiographic Province. The samples were taken from the Taylor Group of the Gulfian Series, Cretaceous System. The Taylor Group is composed predominantly of marl with interbedded chalk and sand. The Taylor Group is underlain by the rather expansive Austin Group and overlain by the Navarro Group. The Taylor Group exhibits lateral variability with respect to thickness (varies from 0 to 900 ft) and the presence of the interbeds. The outcrop area extends west-southwest from San Antonio to the Rio Grande River and north from San Antonio to the Red River.

Sample Description

44. The Taylor Group material sampled is a hard nonindurated, slightly weathered, highly calcareous white (N9) to very light gray (N8) marl. Bedding is not apparent. A few shrinkage cracks are present but there are no visible nonlinear voids. The SEM photographs indicate a moderate particle orientation with wavy stratification.

Description of Climate

45. Wedged between the warm waters of the Gulf of Mexico and the high plateaus and mountain ranges of the North American Continent, Texas has diverse meteorological and climatological conditions. Continental, marine, and mountain types of climates are all found in Texas; the continental and mountain types in true form, but the marine climate modified by surges of continental air. The High Plains, separated from the Lower Plains by the Cap Rock Escarpment, lies in a cool-temperature climatic zone. Except for some small areas in the Trans-Pecos, the remainder of the State lies in a warm-temperature subtropical zone. Within these broad zones, six subclasses appropriately identify the climates of Texas. The proximity to the Gulf of Mexico, the persistent southerly and southeasterly flow of warm tropical maritime air into Texas from around the westward extension of the Azores High, and adequate rainfall, combine to produce a humid subtropical climate with hot summers across

the eastern third of the State. The Gulf moisture supply gradually decreases westward and is cut off more frequently during the colder months by intrusions of drier polar air from the north and west; as a result, most of central Texas, as far north as the High Plains, has a subtropical climate with dry winters and humid summers. This region is semiarid. As the distance from the Gulf increases westward, the summer moisture supply continues to decrease gradually, producing a subtropical steppe climate across a broad section along the middle Rio Grande Valley that extends as far west as the Pecos Valley, where rainfall is most often inadequate for agriculture without supplemental irrigation. Except for "islands" of cool-temperate, mountain type climates at the higher elevations in the Guadalupe, Davis, and Chisos Mountains, the area west of the Pecos is mostly arid subtropical, and rainfall is inadequate for other than desert or semidesert types of vegetation. The mountain climates in the Trans-Pecos are cooler throughout the year than those of the adjacent lowlands. Temperatures decrease with altitude and average about 1°F lower for each 300 ft of increased elevation. The rate of change varies with the season, being more rapid in summer and greatest during the warmer hours of the day.

46. Stretching over the largest level plain of its kind in the United States, the High Plains rise gradually from about 2700 ft on the east to more than 4000 ft in spots along the New Mexico border. The combination of high elevation, remoteness from moisture source regions, and frequent intrusions of dry polar air masses result in a dry steppe climate with relatively mild winters. This region is semiarid and rainfall is often inadequate for profitable agricultural production without supplemental irrigation.

47. While the changes in climate across Texas are considerable, they are nevertheless gradual; no natural boundary separates the moist east from the dry west or the cool north from the warm south.

48. Rainfall in Texas is not evenly distributed over the State and varies greatly from year to year. Average annual rainfall along the Louisiana border exceeds 56 in., and in the western extremity of the State, is less than 8 in. In the way of extremes, Clarksville, in

northeast Texas, recorded 109.38 in. in 1873, while Wink, in extreme west Texas, recorded only 1.76 in. in 1956. The number of days with measurable precipitation follows the general trend of rainfall totals so that seasonal frequencies are lowest where amounts are lowest. At a single location amounts for any 1 month will nearly always vary widely from the mean or normal precipitation. Except along the upper Texas coast, it is possible for one or two thunderstorms to account for the entire month's rainfall at a station. Torrential rains of 10 to 20 in. or more may accompany a tropical storm as it moves inland across the Texas coast. These infrequent but excessive amounts are reflected in mean rainfall data and seriously limit the usefulness of this type of statistic in describing rainfall.

49. Patterns of seasonal precipitation in Texas vary considerably for different areas of the State. Rains occur most frequently in late spring as a result of squall-line thunderstorms; consequently, most areas of the State show a peak in May. This includes most of the High and Low Rolling Plains, the Edwards Plateau, north-central, and south-central Texas. Rainfall in the Pecos Valley, most of southern Texas, the lower Rio Grande Valley, and in the coastal section shows a peak in September, with a secondary peak in May. On the High Plains, particularly the northern portion, a significant percentage of the total annual precipitation occurs during the summer months (following the May peak). Throughout the central part of the State, July and August are relatively dry months. In the mountainous Trans-Pecos area of west Texas, afternoon thundershowers during July, August, and September account for most of the annual rainfall. Throughout most of east Texas (east of about 95° west longitude) rainfall is fairly evenly distributed throughout the year. East of about 96° west longitude, annual rainfall exceeds average potential evapotranspiration. West of this meridian, average potential evapotranspiration exceeds annual average rainfall.

50. In most of Texas a large portion of the annual rainfall occurs within short periods of time, resulting in excessive runoff and frequently producing damaging floods.

51. The vast land area of Texas experiences a wide range of

temperatures. The High Plains experience rather low temperatures in winter, while there are several separate areas within the State that experience very high temperatures in summer. The average January temperatures in Amarillo, in the Panhandle, is 36.7°F and at Brownsville, in the lower Rio Grande Valley, 61.4°F. From November through March, surges of cold air from the north are frequent. These cold fronts, or "northers" as they are called locally, modify rapidly as they reach warmer latitudes. Fast moving cold fronts, followed by rapid warming, result in frequent and pronounced temperature changes from day to day, and sometimes from hour to hour, during the colder months of the year.

52. Extended periods of subfreezing temperatures are rare, even on the High Plains. Cold spells that seriously interfere with outdoor activities usually do not last more than 48 to 72 hr at the most. In south Texas, subfreezing temperatures associated with arctic air masses ordinarily are confined to several hours prior to sunrise, and seasons may pass with no subfreezing temperatures at all. Temperatures of 32°F or lower occur only about 3 years out of 4, on an average, in the lower Rio Grande Valley. Extremely cold spells were experienced in south Texas in 1951 and again, 11 years later, in 1962. Brownsville experienced 65 consecutive hr of subfreezing temperatures January 29-February 1, 1951, and 64 consecutive hr January 9-12, 1962.

53. In summer, the temperature contrast is much less pronounced from north to south with daily highs generally in the 90's. August is the hottest month. Extremely hot daytime temperatures occur with greatest frequency in the triangle in south Texas bounded by Rio Grande City, Cotulla, and Eagle Pass, and in an area along the upper Rio Grande from about Presidio northward to Candelaria. Almost as hot, is a small area along the Red River bounded by Childress and Chillicothe, Texas, and Hollis and Altus, Oklahoma.

54. Relative humidity is highest in the coastal region, and decreased gradually inland, as the distance from the Gulf of Mexico increases. Mean annual relative humidity at noon, Central Standard Time, varies from slightly more than 60 percent near the coast to around 35 percent in the El Paso area. On the whole, there is a range of

approximately 10 percent between the high summer and low winter averages. As temperatures increase relative humidities generally decrease, and when temperatures fall the relative humidity tends to rise. The lowest relative humidities are found generally in the daytime, especially in the afternoon, while the highest values usually occur in the early morning.

55. Sunshine is abundant in the extreme southwestern section of the State, decreasing gradually eastward. On an average, the western Trans-Pecos receives 80 percent of the total possible sunshine annually, while the upper coast receives only 60 percent.

Climatic Data Summary

Reporting Station: San Antonio Weather Service Office (41-7945-07)

Mean Monthly Temperature and Normal
Monthly Precipitation for Period 1941-70:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature, °F	50.7	54.5	60.8	69.6	76.0	82.2	84.7	84.7	79.3	70.5	59.7	53.2	68.8
Precipitation, in.	1.66	2.06	1.54	2.54	3.07	2.79	1.69	2.41	3.71	2.84	1.77	1.46	27.54

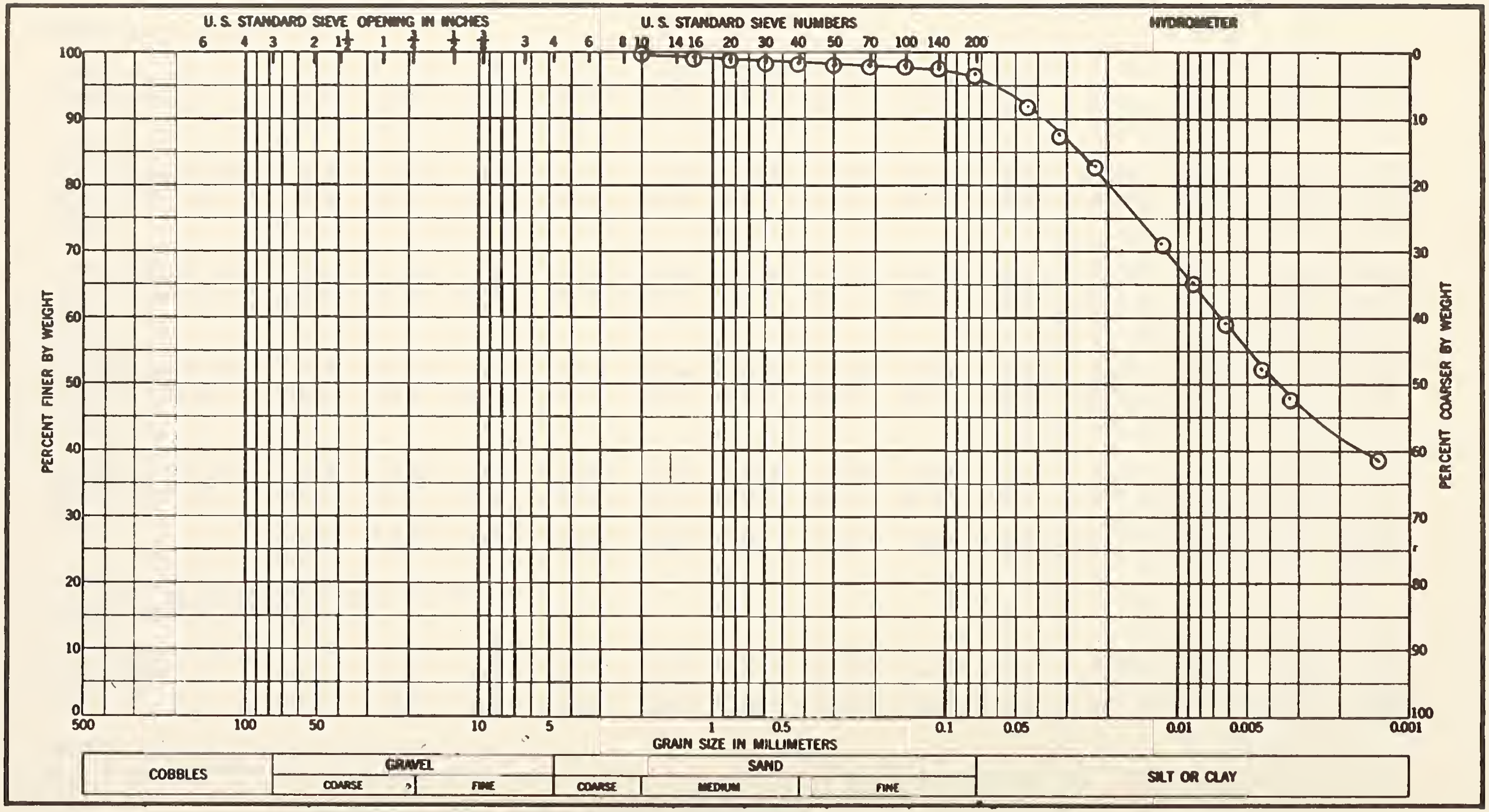
Average Monthly Temperature and
Total Monthly Precipitation for 1971-75:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1971													
Temperature, °F	56.0	57.4	64.6	69.4	78.1	83.6	85.9	81.2	80.1	73.9	63.2	57.2	70.9
Precipitation, in.	0.04	0.81	0.04	1.39	1.52	2.74	1.05	9.42	4.57	4.62	2.74	2.86	31.80
1972													
Temperature, °F	52.8	56.7	66.3	73.7	72.8	80.3	82.2	82.1	82.0	71.9	54.0	50.3	68.8
Precipitation, in.	1.35	0.40	0.13	1.79	11.24	2.86	3.13	4.24	1.40	1.99	2.37	0.44	31.49
1973													
Temperature, °F	47.2	51.9	66.1	66.0	74.7	79.2	83.2	82.1	79.3	72.5	65.8	52.2	68.4
Precipitation, in.	2.77	2.76	1.58	5.41	2.73	10.44	6.91	1.29	13.09	4.85	0.29	0.16	52.28
1974													
Temperature, °F	51.0	56.5	67.9	69.7	77.3	79.4	83.0	81.2	72.3	68.2	57.3	50.9	67.9
Precipitation, in.	1.36	0.04	0.94	2.18	4.28	1.02	1.28	11.14	3.85	4.09	5.39	1.43	37.00
1975													
Temperature, °F	53.2	53.5	61.4	68.4	73.5	80.0	80.9	81.7	76.0	71.1	60.3	53.1	67.8
Precipitation, in.	1.04	3.30	0.52	2.69	6.91	4.60	1.06	1.28	0.51	2.25	0.03	1.48	25.67

Thornthwaite Moisture Index:

1970	1971	1972	1973	1974	1975
1.46	-18.50	5.19	15.73	-1.48	2.87

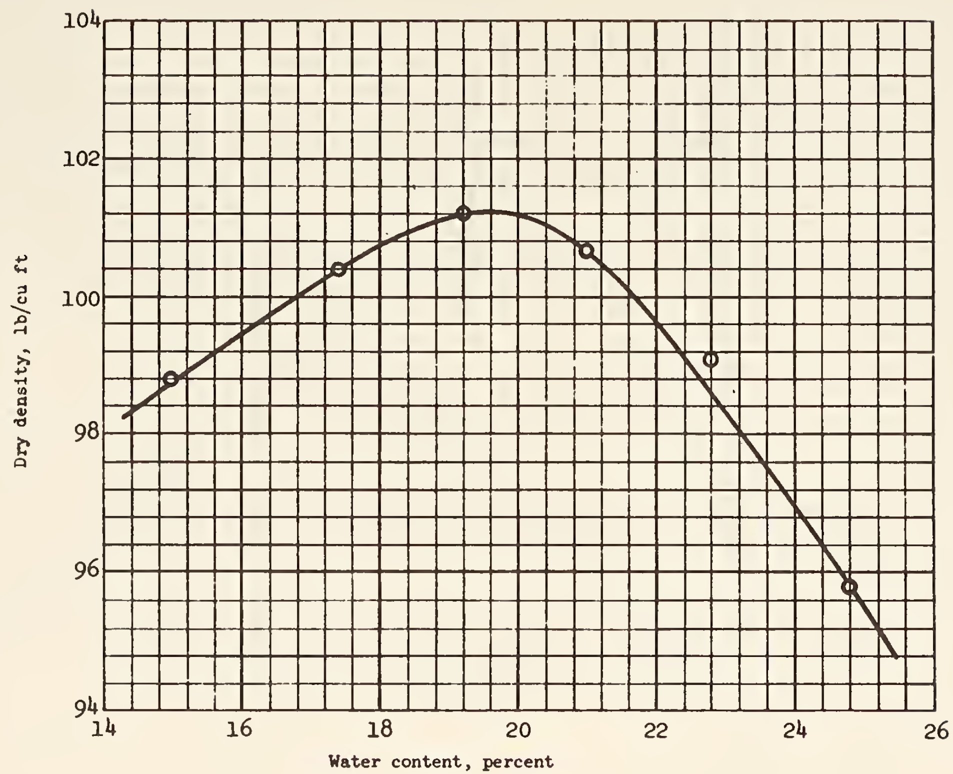
Avg = 0.88



GRADATION CURVE

SITE San Antonio, Tex. BORING U-2

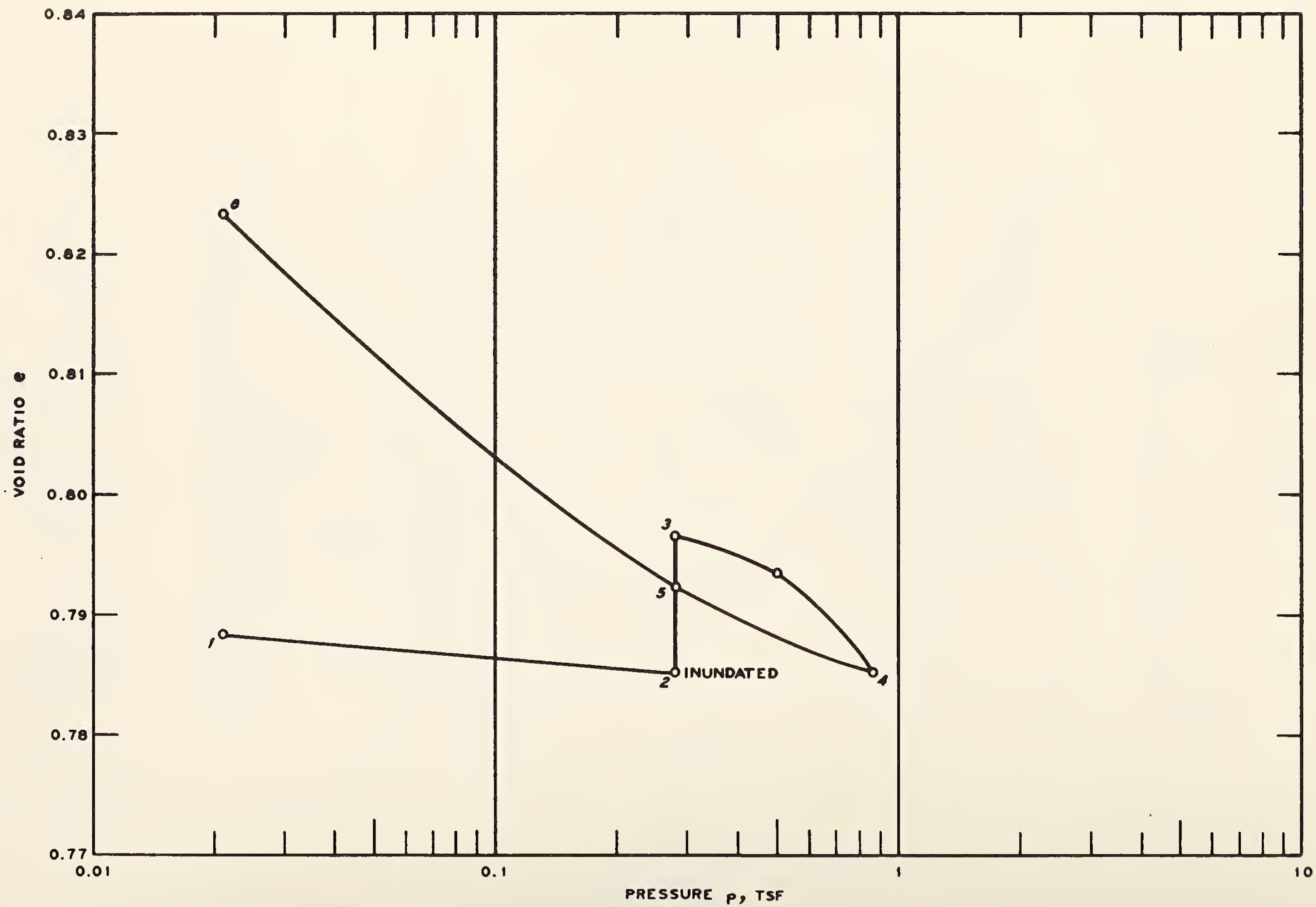
SAMPLE No. 4 DEPTH 3.5-5.1 ft



COMPACTION CURVE

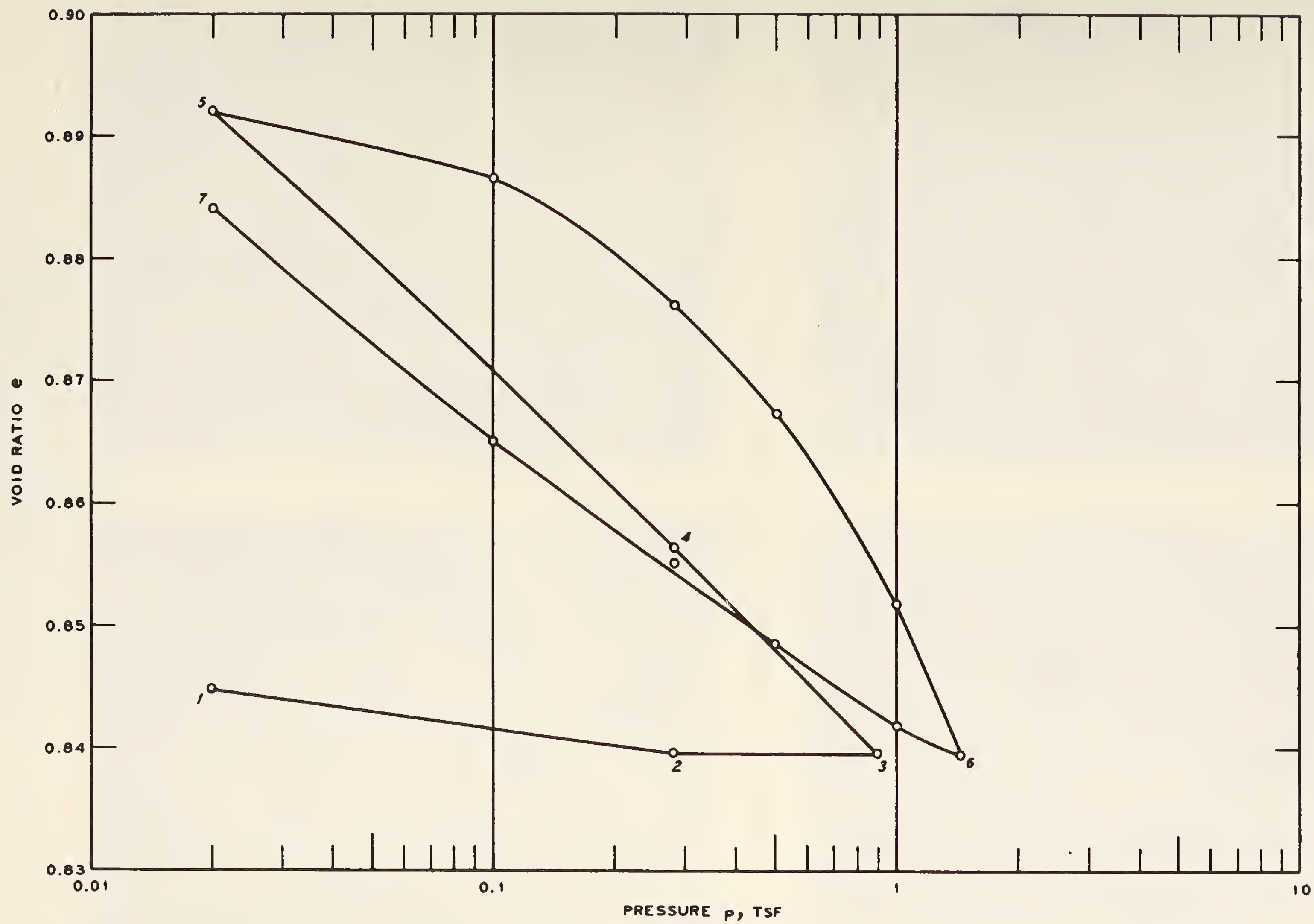
SITE <u>San Antonio, Tex.</u>

SAMPLE <u>Disturbed</u>



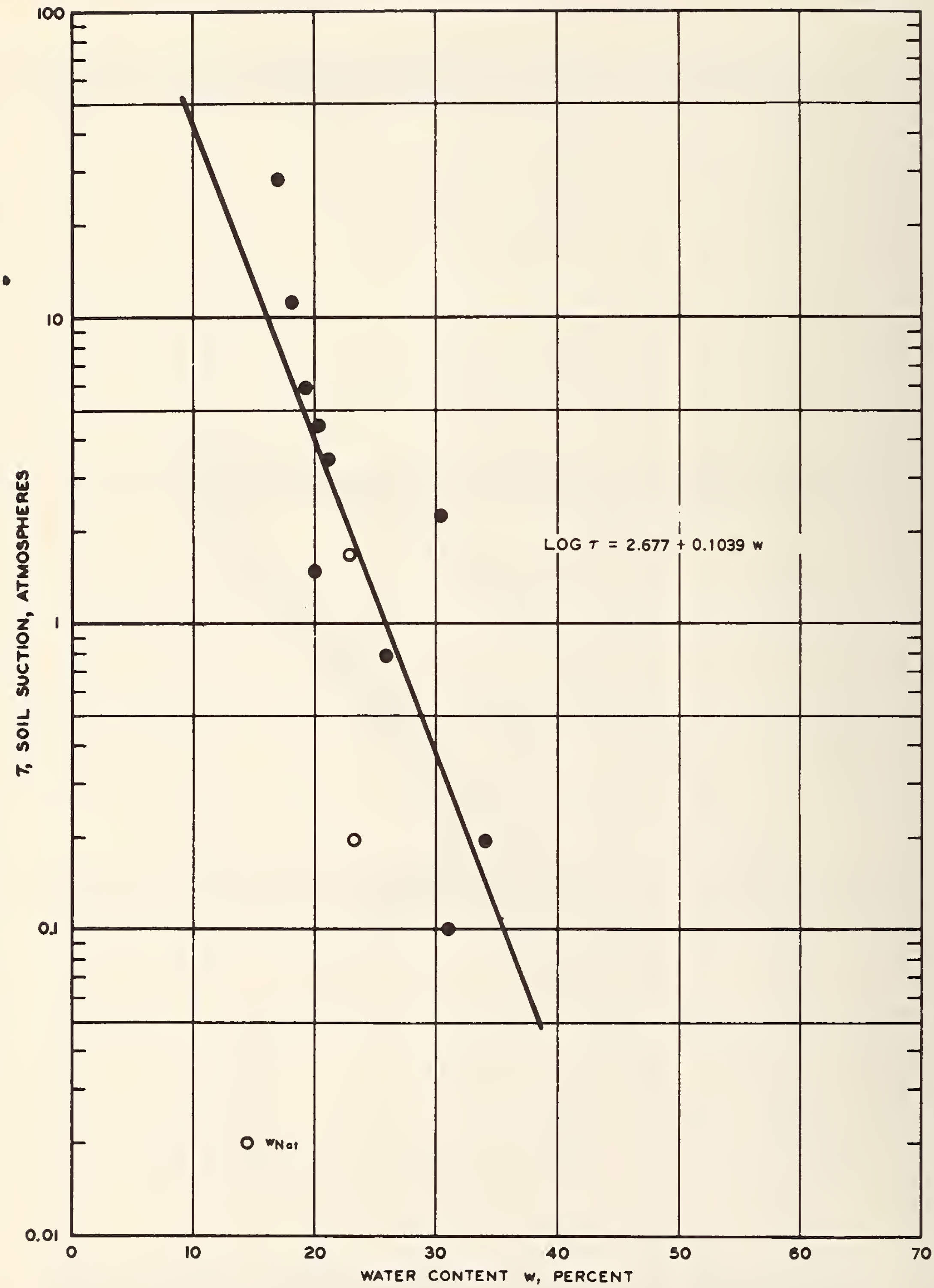
OVERBURDEN SWELL TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

SITE San Antonio, Tex. BORING U-2 SAMPLE No. 4 DEPTH 3.5-5.1 ft



CONSTANT VOLUME SWELL PRESSURE TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

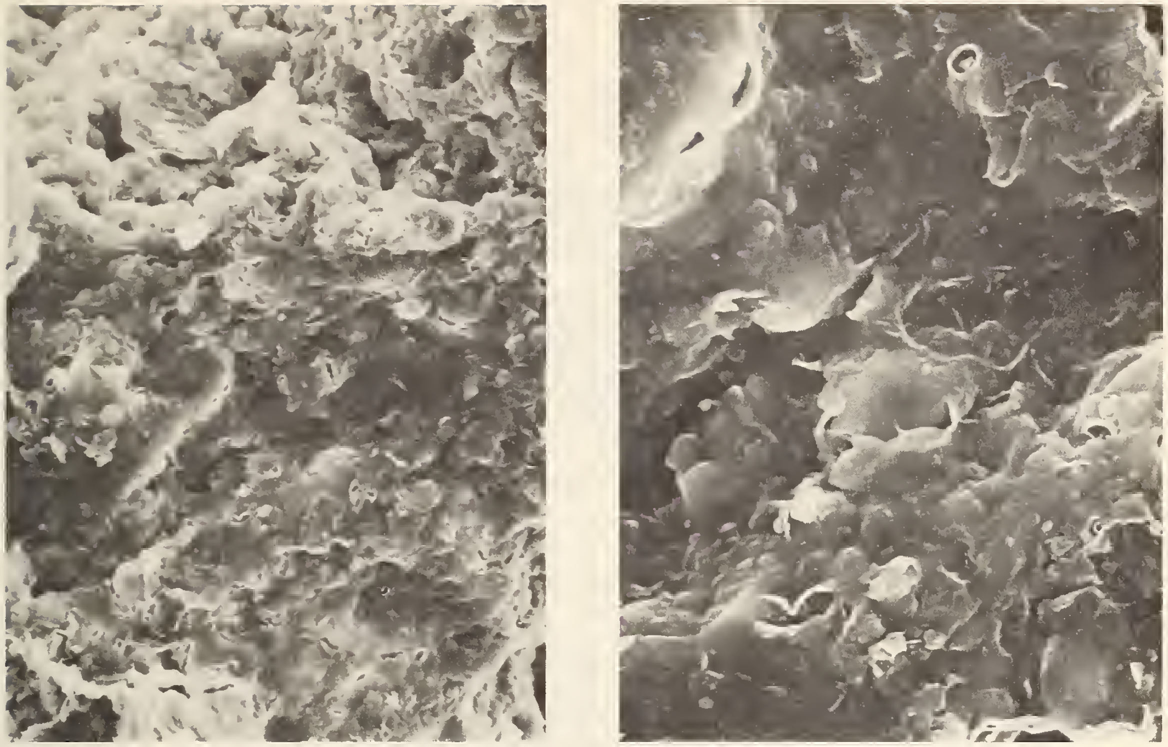
SITE San Antonio, Tex. BORING U-2 SAMPLE No. 4 DEPTH 3.5-5.1 ft



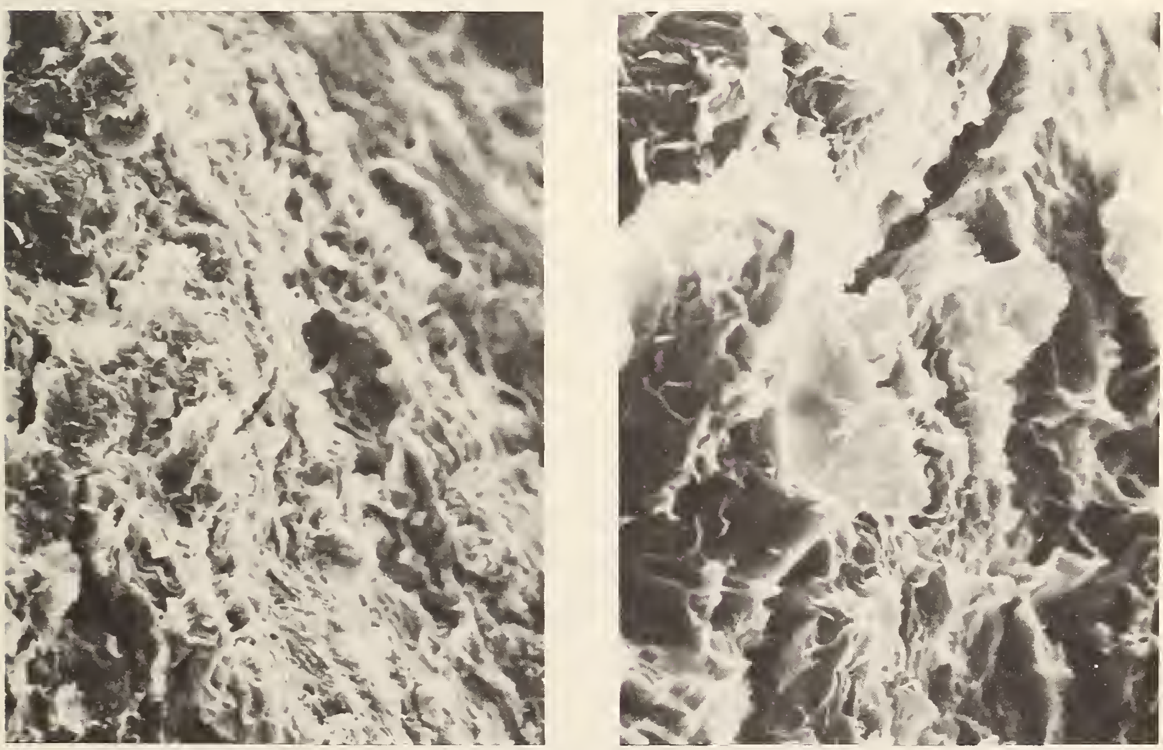
SOIL SUCTION VERSUS WATER CONTENT

SITE San Antonio, Tex. BORING U-2

SAMPLE No. 4 DEPTH 3.5-5.1 ft



a. Normal to Y, ×650 and ×2300



10 μm

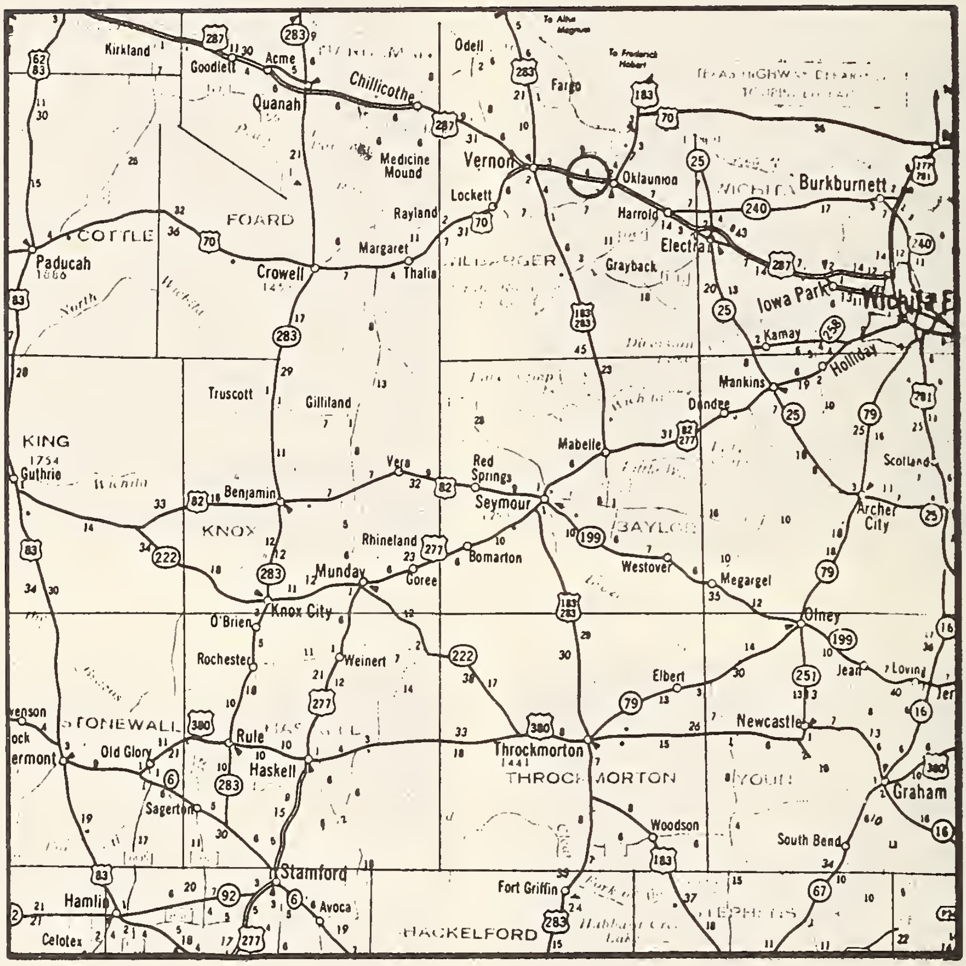
b. Normal to X, ×650 and ×2300

10 μm

SITE San Antonio, Tex. BORING U-2

SAMPLE No. 4 DEPTH 3.5-5.1 ft

SAMPLING SITE NO. 6, VERNON, TEX.



Site Location Information

56. Sampling site No. 6 is located in northern Texas, approximately 7 miles from Vernon, Tex. The site is located approximately 1000 ft west of the U. S. 287 and FM 925 junction. Samples were taken in right-of-way of U. S. 287 (approximately 45 ft southwest of centerline).

Site Description

57. Sampling site is located at grade in open gently rolling terrain. Drainage is in a southerly direction on a very gentle slope. Surrounding area has no vegatative (grass or trees) cover.

Site Geology

58. Sampling site is located in the Osage Plains Section of the Central Lowlands Physiographic Province. The topography of the area indicates low relief with gently rolling low hills. Samples were taken from the Vale Formation of the Clear Fork Group, Upper Leondardian Series, Permian System. The Vale Formation consists of approximately 350 ft of red shale overlain by dolomite, anhydrite, and shale (Choza Formation) and underlain by shale, limestone, and dolomite (Arroyo Formation). The Vale Formation contains some dolomite and anhydrite facies. The outcrop area of the Vale Formation extends south in Texas to the Cretaceous overlap near San Angelo. The Clear Fork Group is the time equivalent of the Hennessey Shale in Oklahoma.

Sample Description

59. The Vale Formation near Vernon, Tex., is a hard, indurated, partially weathered noncalcareous, pale reddish brown (10 R 5/4) siltstone or silt shale. Bedding, fractures, and voids are not apparent under the binocular microscope. White circular spots (radius of $\approx$ 1 mm) occurs throughout the sample. The SEM photographs show a massive appearance lacking appreciable well-defined platelets.

Description of Climate

60. Wedged between the warm waters of the Gulf of Mexico and the high plateaus and mountain ranges of the North American Continent, Texas has diverse meteorological and climatological conditions. Continental, marine, and mountain types of climates are all found in Texas; the continental and mountain types in true form, but the marine climate modified by surges of continental air. The High Plains, separated from the Lower Plains by the Cap Rock Escarpment, lies in a cool-temperature climatic zone. Except for some small areas in the Trans-Pecos, the remainder of the State lies in a warm-temperature subtropical zone. Within these broad zones, six subclasses appropriately identify the climates of Texas. The proximity to the Gulf of Mexico, the persistent southerly and southeasterly flow of warm tropical maritime air into Texas from around the westward extension of the Azores High, and adequate rainfall, combine to produce a humid subtropical climate with hot summers across

the eastern third of the State. The Gulf moisture supply gradually decreases westward and is cut off more frequently during the colder months by intrusions of drier polar air from the north and west; as a result, most of central Texas, as far north as the High Plains, has a subtropical climate with dry winters and humid summers. This region is semiarid. As the distance from the Gulf increases westward, the summer moisture supply continues to decrease gradually, producing a subtropical steppe climate across a broad section along the middle Rio Grande Valley that extends as far west as the Pecos Valley, where rainfall is most often inadequate for agriculture without supplemental irrigation. Except for "islands" of cool-temperate, mountain type climates at the higher elevations in the Guadalupe, Davis, and Chisos Mountains, the area west of the Pecos is mostly arid subtropical, and rainfall is inadequate for other than desert or semidesert types of vegetation. The mountain climates in the Trans-Pecos are cooler throughout the year than those of the adjacent lowlands. Temperatures decrease with altitude and average about 1°F lower for each 300 ft of increased elevation. The rate of change varies with the season, being more rapid in summer and greatest during the warmer hours of the day.

61. Stretching over the largest level plain of its kind in the United States, the High Plains rise gradually from about 2700 ft on the east to more than 4000 ft in spots along the New Mexico border. The combination of high elevation, remoteness from moisture source regions, and frequent intrusions of dry polar air masses result in a dry steppe climate with relatively mild winters. This region is semiarid and rainfall is often inadequate for profitable agricultural production without supplemental irrigation.

62. While the changes in climate across Texas are considerable, they are nevertheless gradual; no natural boundary separates the moist east from the dry west or the cool north from the warm south.

63. Rainfall in Texas is not evenly distributed over the State and varies greatly from year to year. Average annual rainfall along the Louisiana border exceeds 56 in., and in the western extremity of the State, is less than 8 in. In the way of extremes, Clarksville, in

northeast Texas, recorded 109.38 in. in 1873, while Wink, in extreme west Texas, recorded only 1.76 in. in 1956. The number of days with measurable precipitation follows the general trend of rainfall totals so that seasonal frequencies are lowest where amounts are lowest. At a single location amounts for any 1 month will nearly always vary widely from the mean or normal precipitation. Except along the upper Texas coast, it is possible for one or two thunderstorms to account for the entire month's rainfall at a station. Torrential rains of 10 to 20 in. or more may accompany a tropical storm as it moves inland across the Texas coast. These infrequent but excessive amounts are reflected in mean rainfall data and seriously limit the usefulness of this type of statistic in describing rainfall.

64. Patterns of seasonal precipitation in Texas vary considerably for different areas of the State. Rains occur most frequently in late spring as a result of squall-line thunderstorms; consequently, most areas of the State show a peak in May. This includes most of the High and Low Rolling Plains, the Edwards Plateau, north-central, and south-central Texas. Rainfall in the Pecos Valley, most of southern Texas, the lower Rio Grande Valley, and in the coastal section shows a peak in September, with a secondary peak in May. On the High Plains, particularly the northern portion, a significant percentage of the total annual precipitation occurs during the summer months (following the May peak). Throughout the central part of the State, July and August are relatively dry months. In the mountainous Trans-Pecos area of west Texas, afternoon thundershowers during July, August, and September account for most of the annual rainfall. Throughout most of east Texas (east of about 95° west longitude) rainfall is fairly evenly distributed throughout the year. East of about 96° west longitude, annual rainfall exceeds average potential evapotranspiration. West of this meridian, average potential evapotranspiration exceeds annual average rainfall.

65. In most of Texas a large portion of the annual rainfall occurs within short periods of time, resulting in excessive runoff and frequently producing damaging floods.

66. The vast land area of Texas experiences a wide range of

temperatures. The High Plains experience rather low temperatures in winter, while there are several separate areas within the State that experience very high temperatures in summer. The average January temperatures in Amarillo, in the Panhandle, is 36.7°F and at Brownsville, in the lower Rio Grande Valley, 61.4°F. From November through March, surges of cold air from the north are frequent. These cold fronts, or "northers" as they are called locally, modify rapidly as they reach warmer latitudes. Fast moving cold fronts, followed by rapid warming, result in frequent and pronounced temperature changes from day to day, and sometimes from hour to hour, during the colder months of the year.

67. Extended periods of subfreezing temperatures are rare, even on the High Plains. Cold spells that seriously interfere with outdoor activities usually do not last more than 48 to 72 hr at the most. In south Texas, subfreezing temperatures associated with arctic air masses ordinarily are confined to several hours prior to sunrise, and seasons may pass with no subfreezing temperatures at all. Temperatures of 32°F or lower occur only about 3 years out of 4, on an average, in the lower Rio Grande Valley. Extremely cold spells were experienced in south Texas in 1951 and again, 11 years later, in 1962. Brownsville experienced 65 consecutive hr of subfreezing temperatures January 29-February 1, 1951, and 64 consecutive hr January 9-12, 1962.

68. In summer, the temperature contrast is much less pronounced from north to south with daily highs generally in the 90's. August is the hottest month. Extremely hot daytime temperatures occur with greatest frequency in the triangle in south Texas bounded by Rio Grande City, Cotulla, and Eagle Pass, and in an area along the upper Rio Grande from about Presidio northward to Candelaria. Almost as hot, is a small area along the Red River bounded by Childress and Chillicothe, Texas, and Hollis and Altus, Oklahoma.

69. Relative humidity is highest in the coastal region, and decreased gradually inland, as the distance from the Gulf of Mexico increases. Mean annual relative humidity at noon, Central Standard Time, varies from slightly more than 60 percent near the coast to around 35 percent in the El Paso area. On the whole, there is a range of

approximately 10 percent between the high summer and low winter averages. As temperatures increase relative humidities generally decrease, and when temperatures fall the relative humidity tends to rise. The lowest relative humidities are found generally in the daytime, especially in the afternoon, while the highest values usually occur in the early morning.

70. Sunshine is abundant in the extreme southwestern section of the State, decreasing gradually eastward. On an average, the western Trans-Pecos receives 80 percent of the total possible sunshine annually, while the upper coast receives only 60 percent.

Climatic Data Summary

Reporting Station: Vernon (41-9346-02)

Mean Monthly Temperature and Normal
Monthly Precipitation for Period 1941-70:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature, °F	42.3	46.7	53.3	65.0	72.9	81.5	85.7	85.2	77.1	66.1	53.3	45.1	64.5
Precipitation, in.	0.96	1.27	1.41	2.40	4.68	3.22	2.12	1.60	2.73	3.02	1.18	1.06	25.65

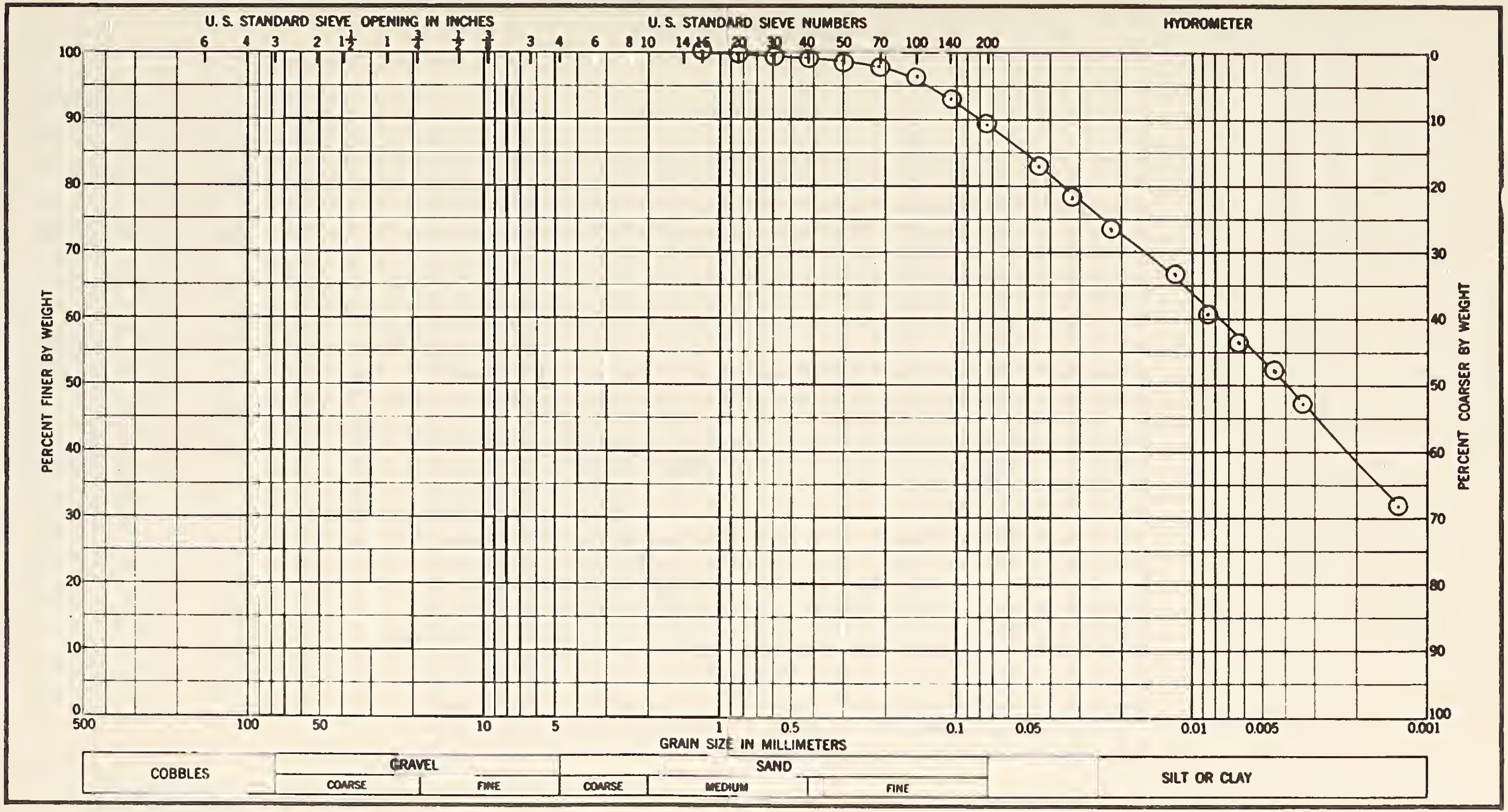
Average Monthly Temperature and
Total Monthly Precipitation for 1971-75:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1971													
Temperature, °F	43.7	47.3	55.3	65.6	73.6	83.1	86.7	79.0	75.2	67.0	55.0	46.5	64.8
Precipitation, in.	0.25	0.70	0.10	0.97	3.47	1.55	0.95	4.42	5.00	3.95	0.92	2.29	24.17
1972													
Temperature, °F	42.6	48.6	60.2	69.2	71.1	82.2	84.1	82.5	77.9	65.0	47.1	41.5	64.3
Precipitation, in.	0.00	0.38	1.86	2.57	3.97	2.10	0.80	3.18	2.12	6.32	1.86	0.00	25.16
1973													
Temperature, °F	37.4	45.6	56.7	58.7	71.5	79.7	84.1	82.7	74.8	68.1	58.0	--*	--
Precipitation, in.	3.31	1.58	4.36	3.41	0.62	2.62	4.83	0.48	6.28	2.05	1.52	0.15	31.21
1974													
Temperature, °F	43.1	51.1	62.5	66.6	78.0	80.7	--*	81.5	69.1	65.1	--*	43.2	--
Precipitation, in.	0.00	0.10	1.05	2.80	2.87	2.12	0.43	3.54	6.01	2.41	0.61	0.65	22.59
1975													
Temperature, °F	45.1	43.8	54.3	63.1	71.8	78.7	--*	81.2	72.1	65.8	--*	47.7	--
Precipitation, in.	1.76	2.01	0.61	1.05	7.49	4.41	8.41	4.47	3.23	1.47	2.36	1.49	38.76

Thornthwaite Moisture Index:

1970	1971	1972	1973	1974	1975	
-26.42	-23.35	-11.21	-0.77	-26.08	2.16	Avg = -14.28

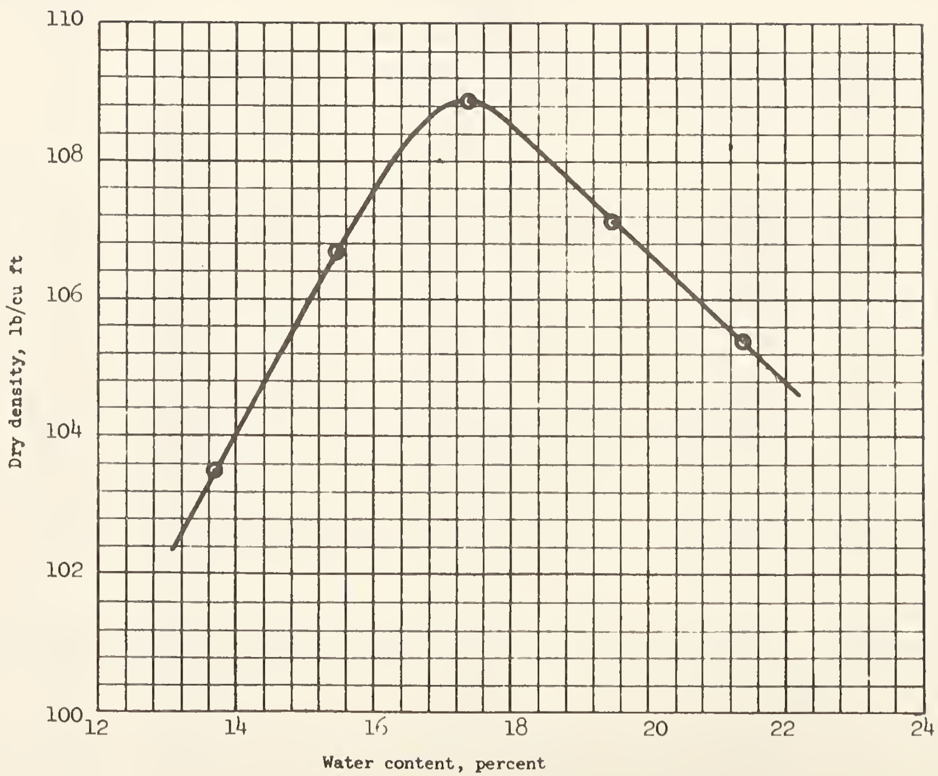
* Record missing.



GRADATION CURVE

SITE Vernon, Tex. BORING U-1

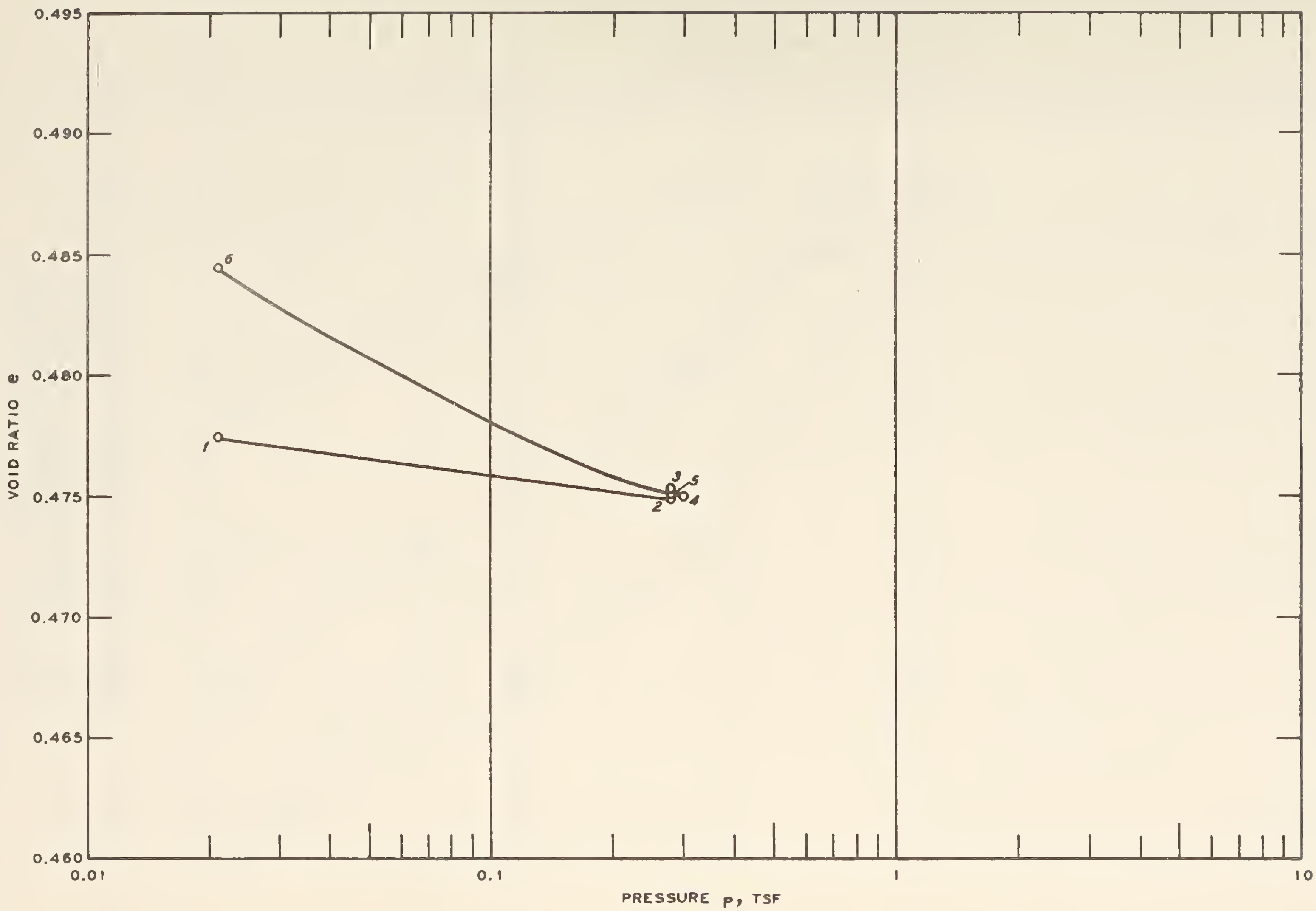
SAMPLE No. 4 DEPTH 4.8-7.2 ft



COMPACTION CURVE

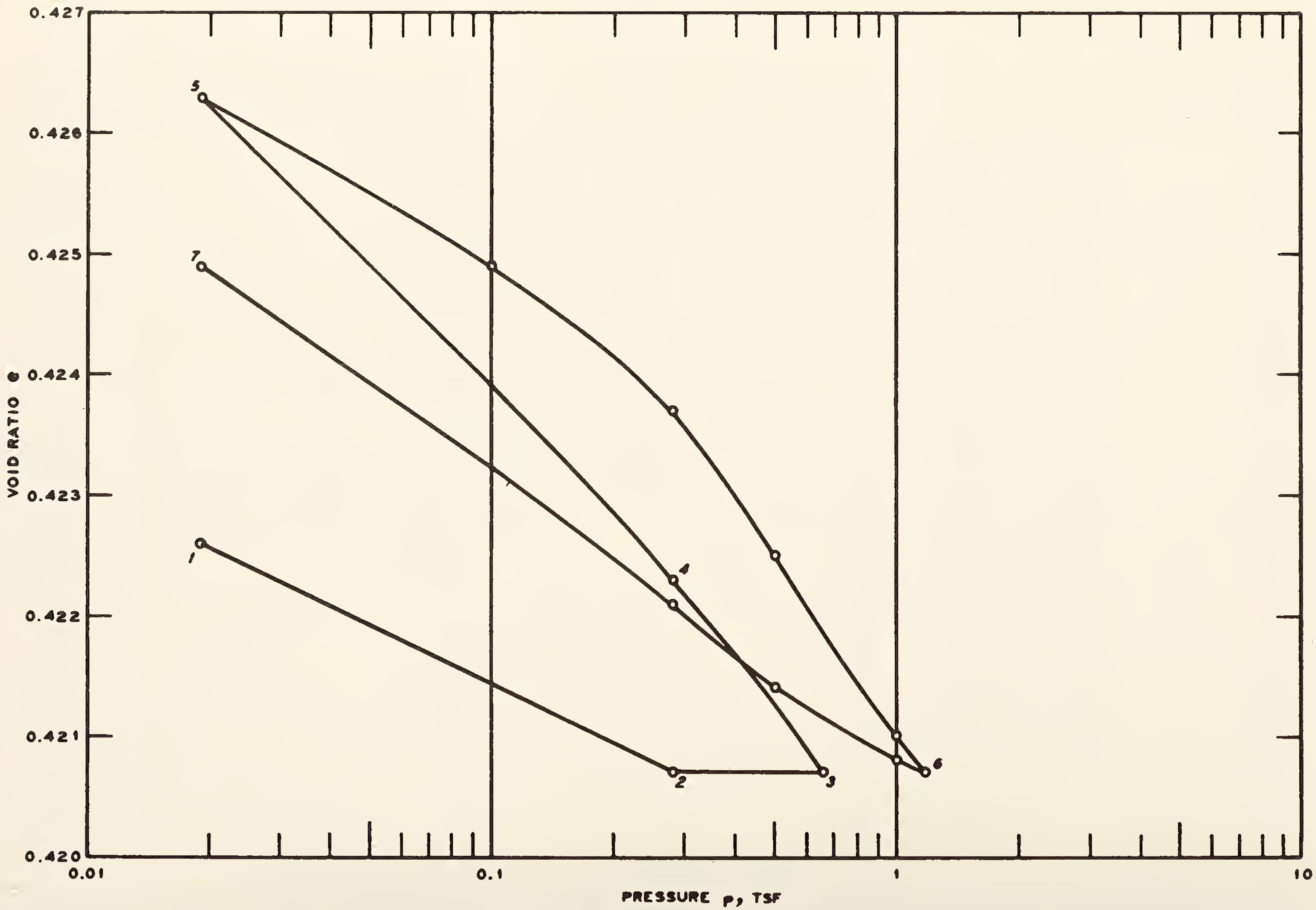
SITE Vernon Tex.

SAMPLE Disturbed



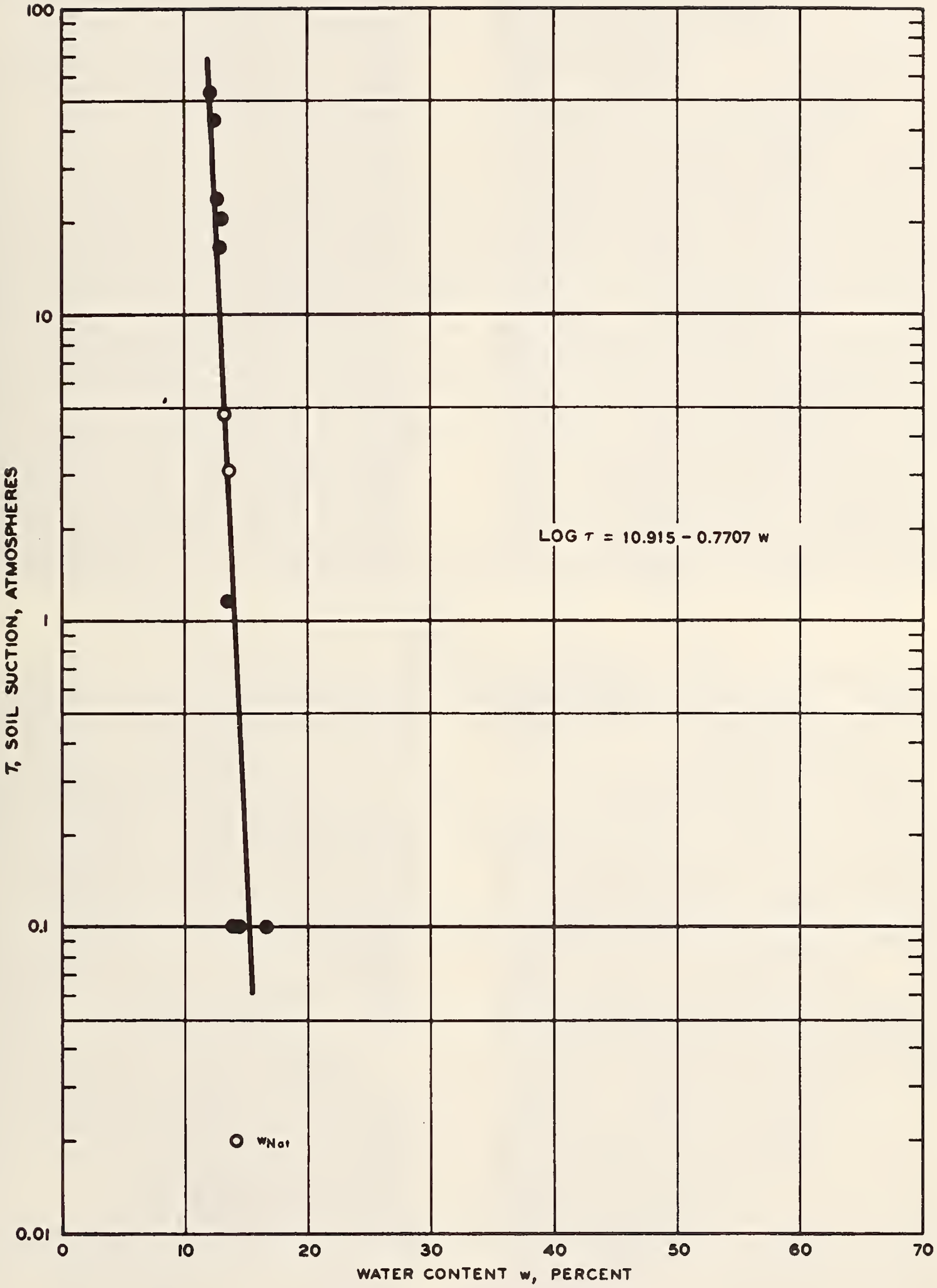
OVERBURDEN SWELL TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

SITE Vernon, Tex. BORING U-1 SAMPLE No. 4 DEPTH 4.8-7.2 ft



CONSTANT VOLUME SWELL PRESSURE TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

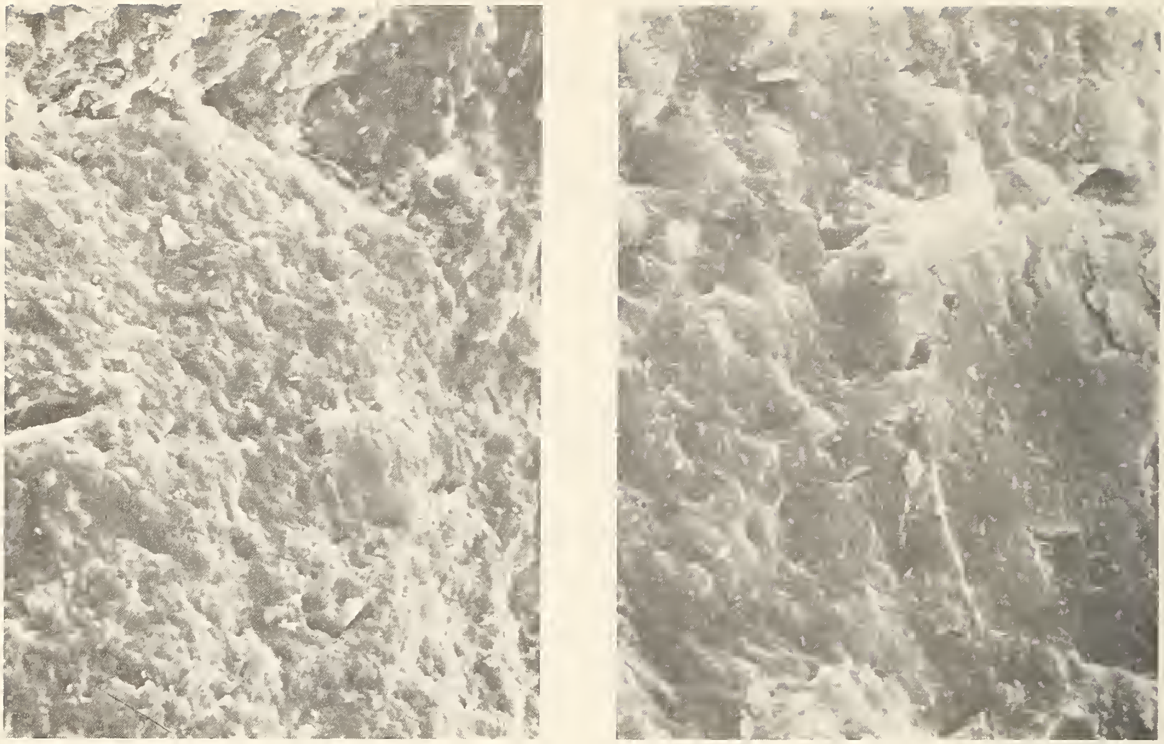
SITE Vernon, Tex. BORING U-1 SAMPLE No. 4 DEPTH 4.8-7.2 ft



SOIL SUCTION VERSUS WATER CONTENT

SITE Vernon, Tex. BORING U-1

SAMPLE No. 4 DEPTH 4.8-7.2 ft



a. Normal to Y, ×650 and ×2300

10 μm

b. Normal to X, ×650 and ×2300

10 μm

SITE Vernon, Tex. BORING U-1

SAMPLE No. 4 DEPTH 4.8-7.2 ft

SAMPLING SITE NO. 7, DURANT, OKLA.

Site Location Information

71. Sampling site No. 7 is located in southern Oklahoma, approximately 3 miles north of Durant, Okla. (Bryan County). The site is located approximately 1000 ft north of U. S. 69 and 75 and SH 78 junction on SH 78. Samples were taken in west verge slope of southbound lane of SH 78 (200 ft north of SE corner of section 17, T6S, R9E).

Site Description

72. Sampling site is located in a cut section (≈ 20 ft deep) in hilly terrain. Drainage is in a southerly direction on a moderate to steep slope. Surrounding area has a complete grass cover with a sparse tree cover above the cut slope.

Site Geology

73. Sampling site is located in the West Gulf Coastal Plain Section of the Coastal Plain Physiographic Province. Samples were taken in the Washita Group of the Comanchean Series, Cretaceous System which consists of interbedded clay or shale, marl, and limestone. The Washita is overlain by interbedded sands, marls, and limestones of the Comanchean Series and underlain by interbedded shale, limestone, and sand of the Fredericksburg Group. The Washita Group outcrops in a narrow band north of the Red River from Lake Texoma to the Arkansas line.

Sample Description

74. The Washita material sampled is hard, indurated, moderately weathered, noncalcareous, medium dark gray (N4) clay shale with distinct bedding planes. Fractures and visible voids are not apparent. Accessory biotite and muscovite are relatively common. Also present are light gray to yellow silt laminations. The SEM photographs indicate moderate particle orientation with wavy stratification.

Description of Climate

75. The climate of Oklahoma is mostly continental in type, as in all of the central Great Plains. Warm, moist air moving northward from the Gulf of Mexico exerts much influence at times, particularly over the southern and more eastern sections of the State where, as a result, humidities and cloudiness are generally greater and precipitation considerably heavier than in the western and northern sections. Summers are long and occasionally very hot. Winters are shorter and less rigorous than those of the more northern Plain States. Periods of extreme cold are infrequent.

76. The mean annual temperature over the State ranges from 64°F along the southern border to about 60°F along the northern border. It then decreases westward across the Panhandle to about 57°F in Cimarron County. Temperatures of 90°F or higher occur, on an average, about 85 days per year in the western Panhandle and in the northeast corner of the State. In the southwest, the average is about 120 days, and in the southeast from 95 to 100 days. Temperatures of 100°F or higher are common over the State from May well into September. In the southwest

part of the State the average number of 100°F days is 20 to 25 per year. Other sections of the State will average somewhat less, but very seldom will any location in the State not reach a 100°F temperature sometime during the summer months.

77. Low humidities and good southerly breezes usually accompany the high summer temperatures and somewhat lessen their discomforting effect. Occasionally strong, hot winds accompany the high daytime temperatures; this combination produces rapid evaporation.

78. Temperatures of 32°F or less occur on an average of 55 to 65 days per year along the southern tier of counties and from 90 to 100 days per year along the Kansas border in the north-central and northeastern sections of the State. In the Panhandle, days with 32°F or less occur, on an average, 125 to 140 days per year. The lowest temperature of record is -27°F and was observed at Watts on January 18, 1930, and at Vinita on February 13, 1905.

79. Frozen soil is not a major problem, nor much of a deterrent to seasonal activities. Its occurrence is rather infrequent, of very limited extent, and of brief duration. The average maximum depth that frost penetrates the soil ranges from less than 3 in. in the southeastern corner of the State to more than 10 in. in the extreme northwestern portion. Extreme frost penetration ranges from 10 in. in the southeast corner to about 30 in. in the northwest corner of the Panhandle. Factors having an important bearing on frost penetration are severity and duration of temperature below freezing; condition, character, and moisture content of the soil; and amount and character of protective cover of the soil including snow cover.

80. The geographical distribution of rainfall decreases sharply from east to west. Average annual precipitation ranges from about 56 in. in southern LeFlore County, in the southeastern corner of the State, to 15 in. in the extreme western Panhandle. The greatest annual precipitation recorded at an official reporting station was 84.47 in. at Kiamichi Tower in southern LeFlore County in 1957. The least annual amount was 6.53 in. at Regnier in northwestern Cimarron County in 1956.

81. Frequency of rainfall, as determined from the average number

of days with 0.01 in. or more, varies from 95 to 100 days a year in the extreme east to from 70 to 80 days a year over the western third of the State.

82. Relative humidity averages about 10 percent higher in the eastern portion of the State because of lower elevations and more frequent inflow of Gulf moisture. Summer afternoon and early evening humidities are considerably lower than those of winter.

83. Average annual lake evaporation varies from about 48 in. in the extreme eastern sections of the State to as high as 65 in. in the southwestern corner. In the western Panhandle approximately 58 in. of water is evaporated each year. The importance of these evaporative losses from reservoirs and other surface water supplies has prompted a good deal of research to find ways of retarding the evaporation process.

84. Prevailing winds are southerly although northerly winds predominate during the winter months. Average yearly wind speeds vary from 9 mph in the east to approximately 14 mph in the west. March and April are the windiest months, and July and August the calmest.

Climatic Data Summary

Reporting Station: Durant SE State College (34-2678-08)

Mean Monthly Temperature and Normal
Monthly Precipitation for Period 1941-70:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature, °F	42.3	46.5	53.0	64.0	71.0	78.7	82.8	82.7	75.1	65.1	53.5	44.9	63.3
Precipitation, in.	1.86	2.76	2.98	4.91	5.32	3.98	2.90	2.49	4.52	3.41	2.74	2.35	40.22

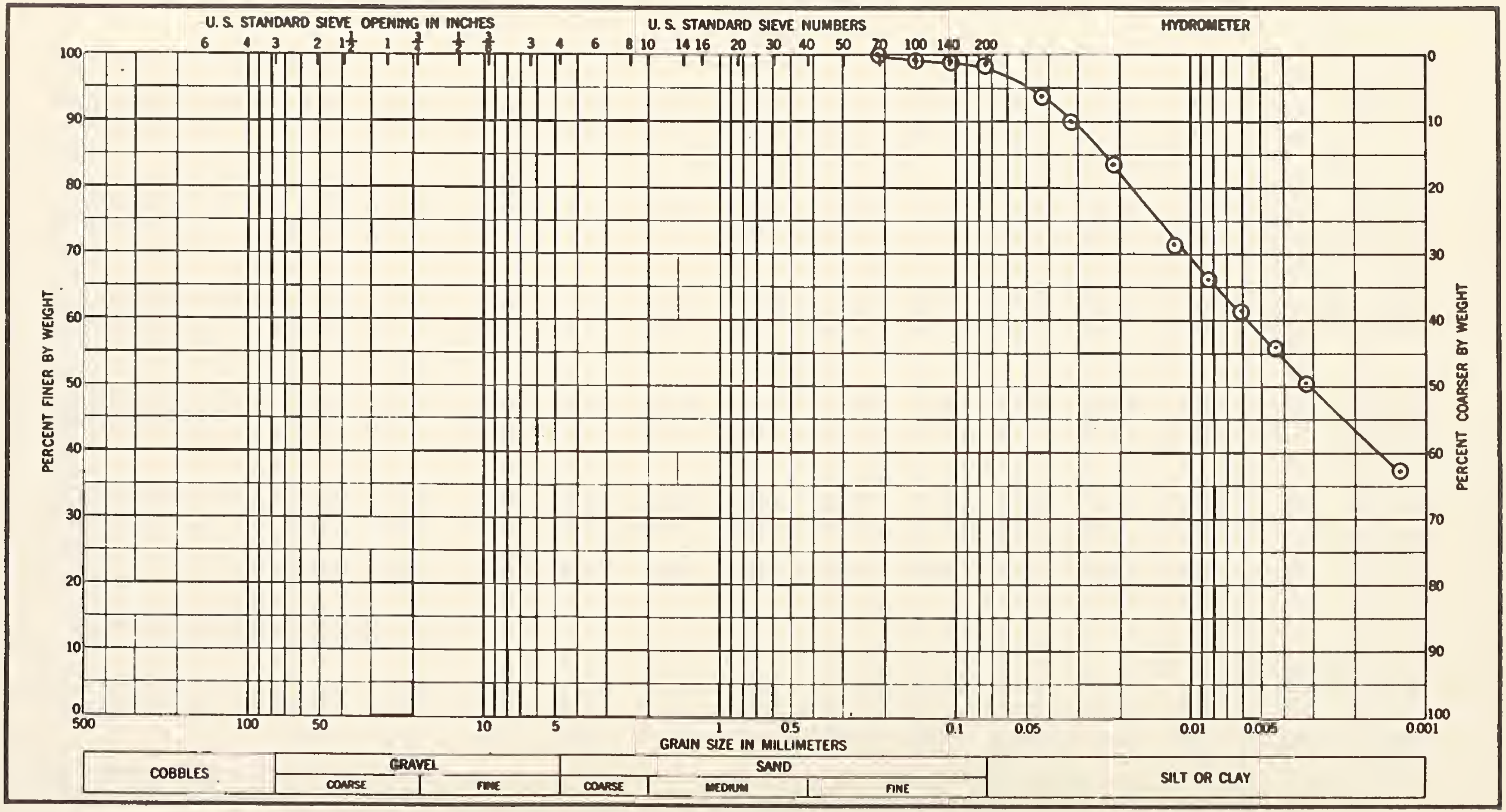
Average Monthly Temperature and
Total Monthly Precipitation for 1971-75:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1971													
Temperature, °F	44.5	46.7	54.2	63.1	69.1	80.3	83.0	77.9	75.3	67.5	53.6	47.4	63.6
Precipitation, in.	0.86	1.69	1.26	3.45	6.20	1.96	2.20	5.59	8.60	7.34	2.87	7.35	49.37
1972													
Temperature, °F	39.5	48.1	59.2	66.1	69.6	78.6	81.5	82.0	78.6	64.4	46.3	40.4	62.9
Precipitation, in.	0.45	0.43	0.98	4.34	5.18	1.79	1.28	3.58	7.97	9.03	3.88	0.53	39.44
1973													
Temperature, °F	39.6	44.6	58.0	59.7	70.7	76.7	81.5	80.8	74.8	67.0	57.1	45.4	63.0
Precipitation, in.	1.88	3.05	6.54	7.47	3.29	8.06	3.79	1.01	11.45	4.28	2.87	2.33	56.02
1974													
Temperature, °F	40.6	50.8	60.9	65.3	--*	76.6	83.8	79.7	66.9	66.0	52.3	43.7	--
Precipitation, in.	1.21	1.40	1.23	3.67	2.87	3.60	0.44	8.43	8.23	8.11	3.80	1.76	44.75
1975													
Temperature, °F	--*	44.2	49.8	62.8	71.3	78.1	81.3	82.6	71.5	--*	55.7	--*	--
Precipitation, in.	2.92	2.14	3.98	1.89	6.51	6.24	1.66	1.90	4.64	0.60	3.53	1.50	37.51

Thornthwaite Moisture Index:

1970	1971	1972	1973	1974	1975	
4.96	5.84	-3.30	52.63	18.75	31.75	Avg = 18.44

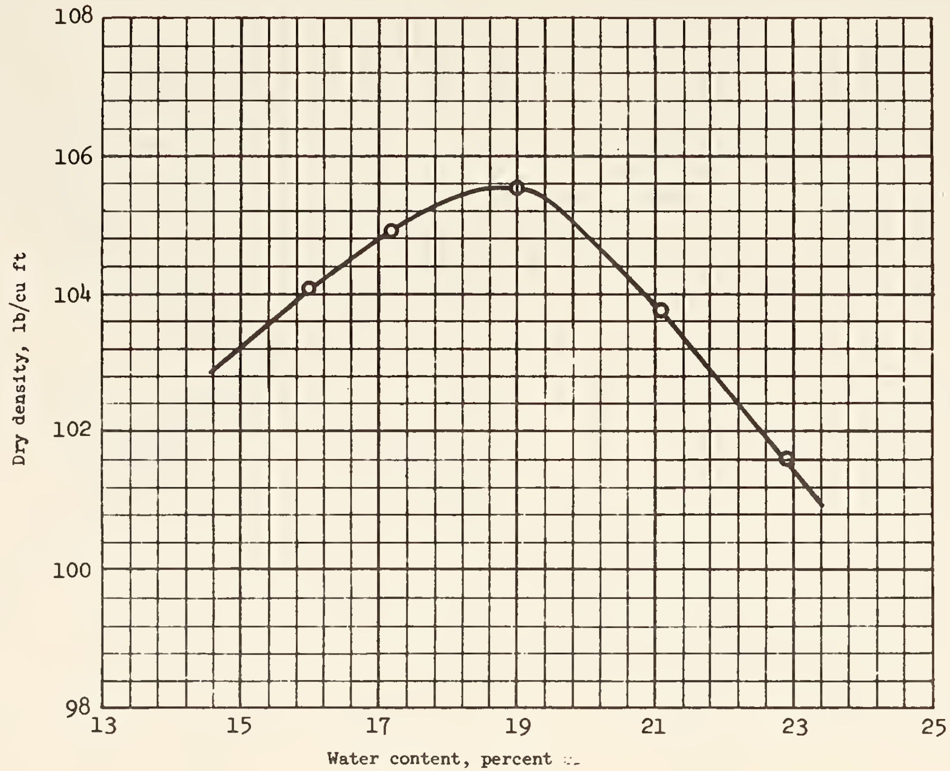
* Record missing.



GRADATION CURVE

SITE Durant, Okla. BORING U-2

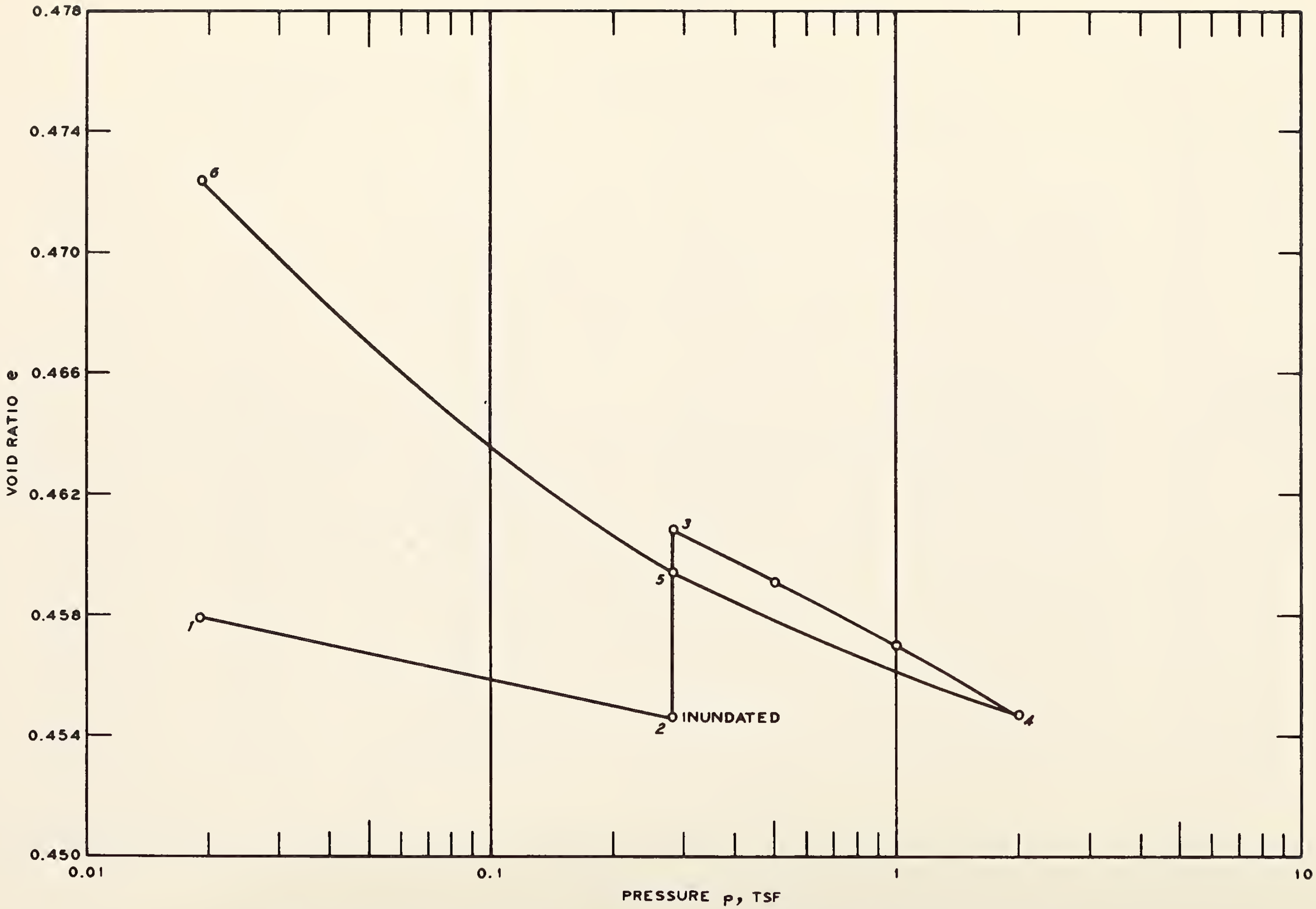
SAMPLE No. 2 DEPTH 3.5-4.7 ft



COMPACTION CURVE

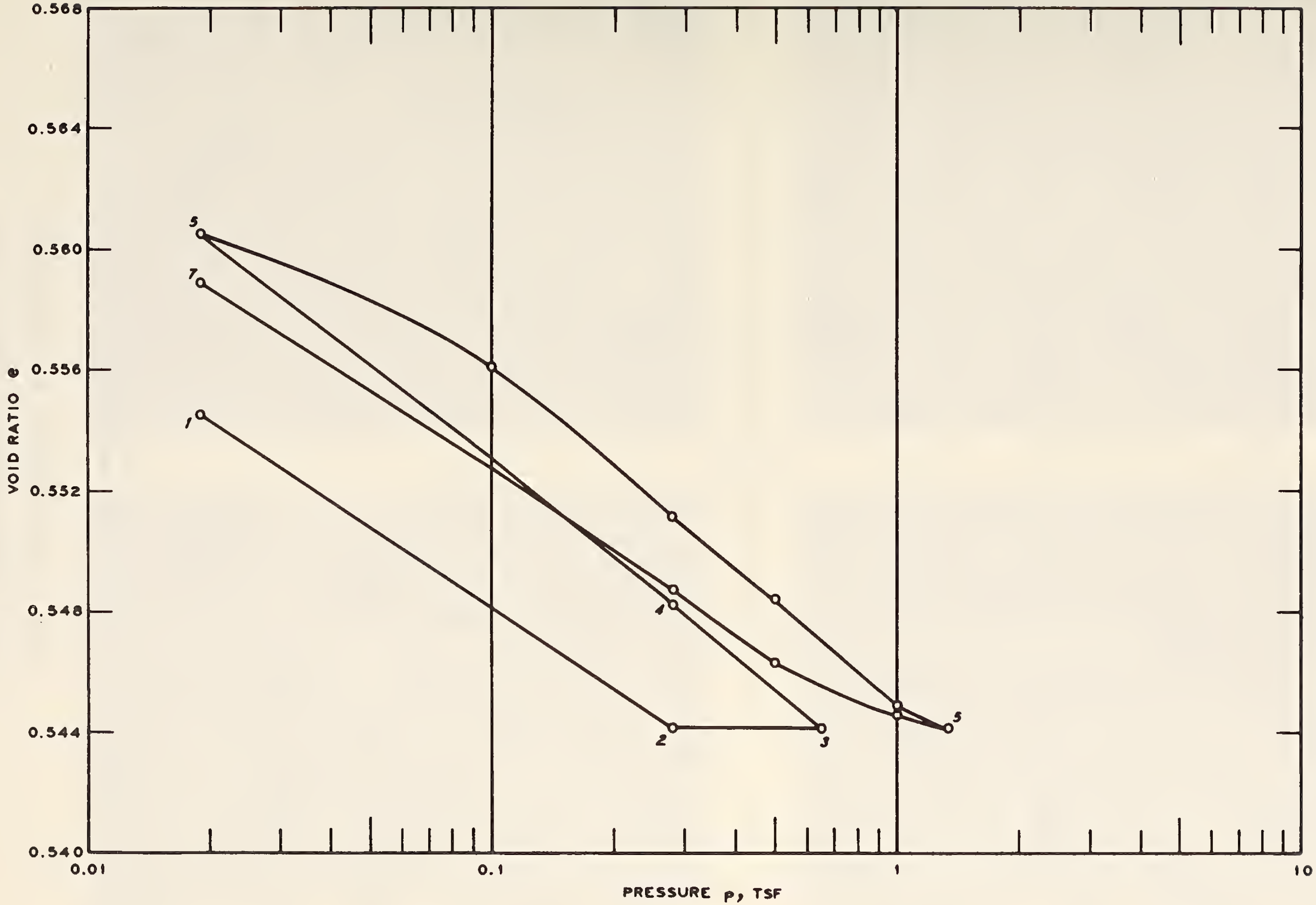
SITE Durant, Okla.

SAMPLE Disturbed



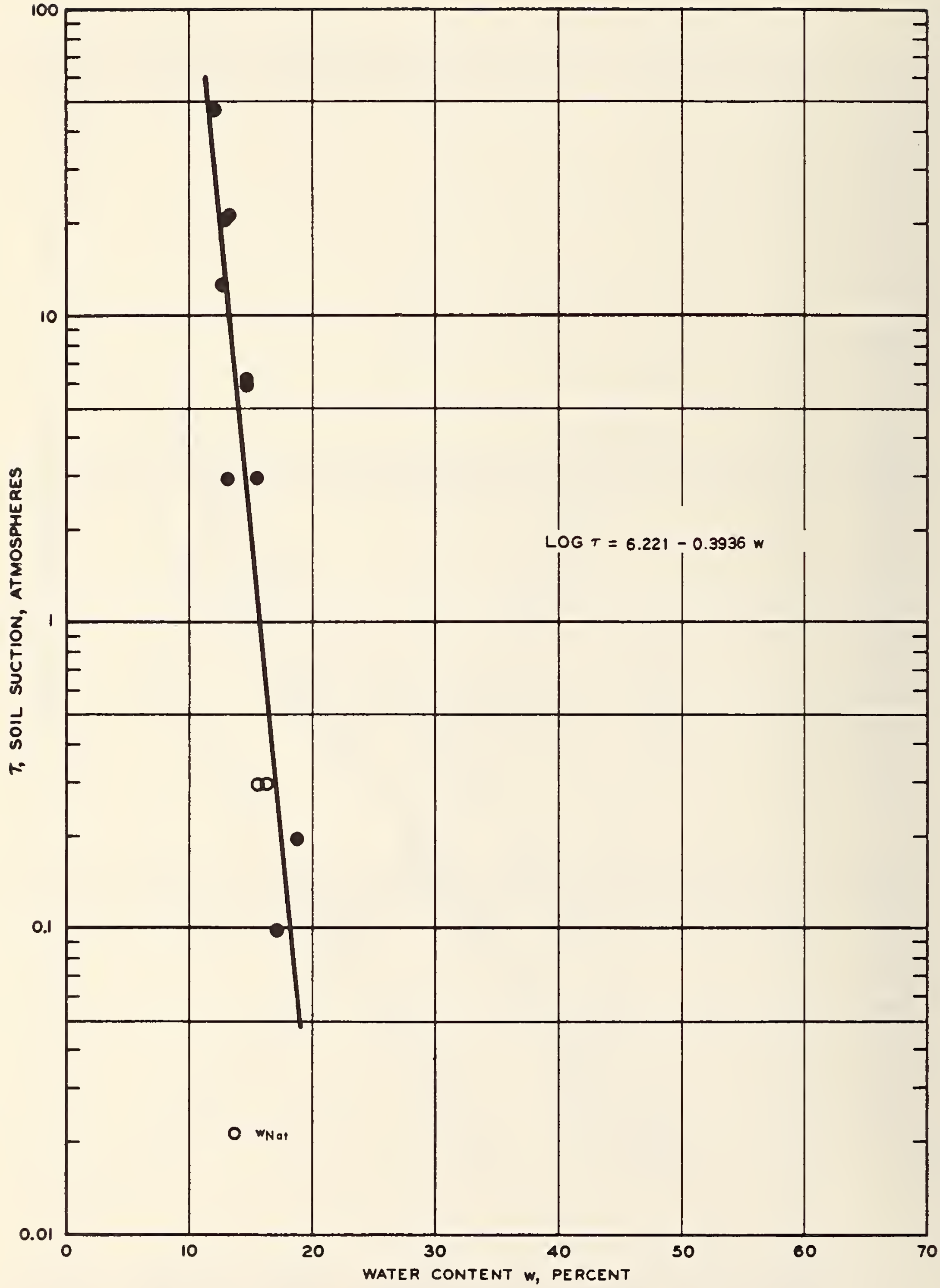
OVERBURDEN SWELL TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

SITE Durant, Okla. BORING U-2 SAMPLE No. 2 DEPTH 3.5-4.7 ft



CONSTANT VOLUME SWELL PRESSURE TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

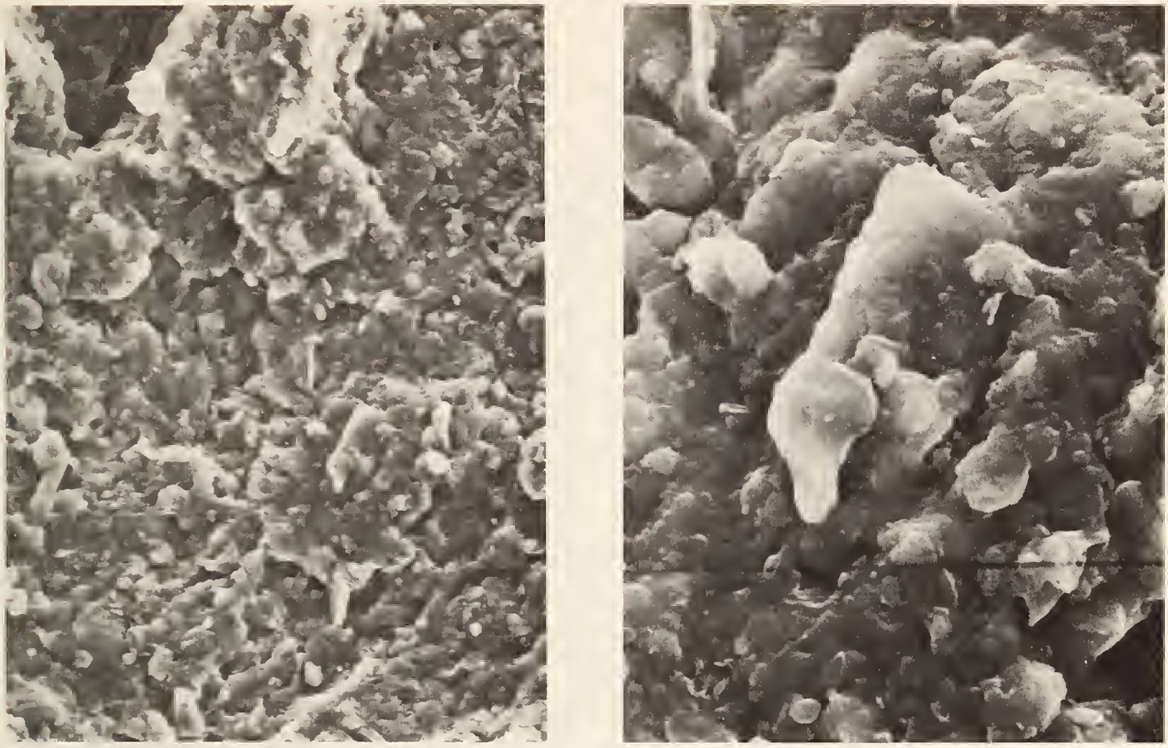
SITE Durant, Okla. BORING U-2 SAMPLE No. 2 DEPTH 3.5-4.7 ft



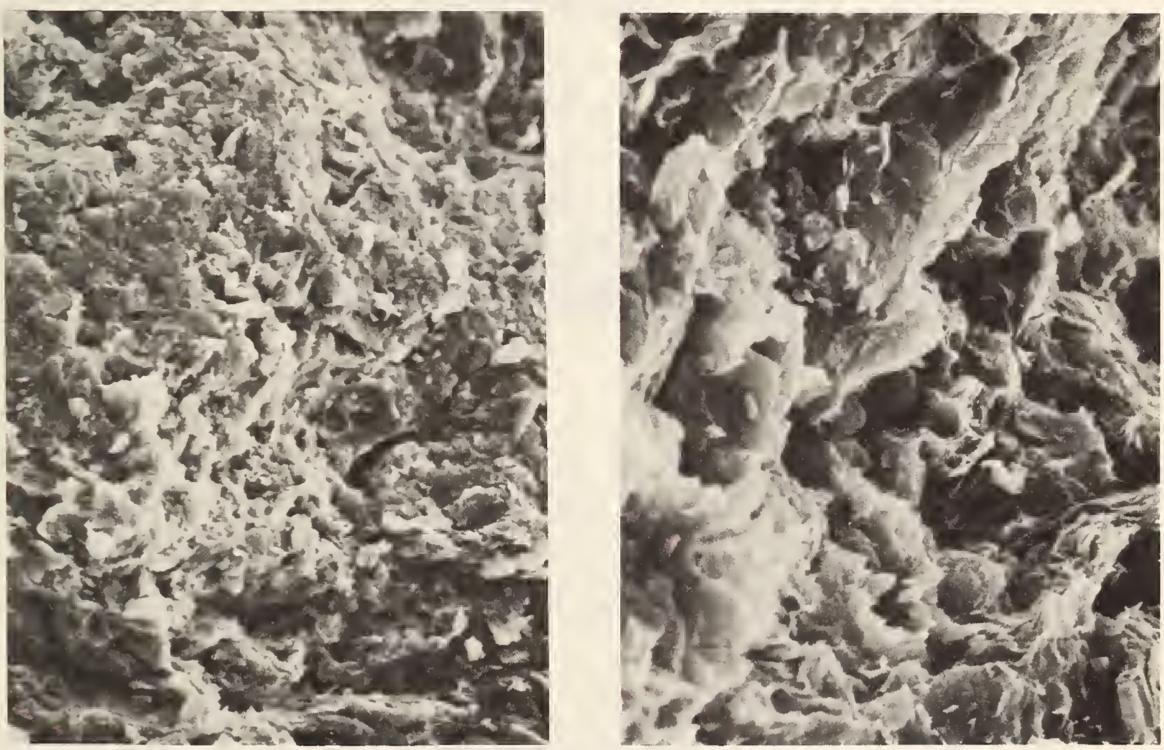
SOIL SUCTION VERSUS WATER CONTENT

SITE Durant, Okla. BORING U-2

SAMPLE No. 2 DEPTH 3.5-4.7 ft



a. Normal to Y, ×650 and ×2300



10 μm

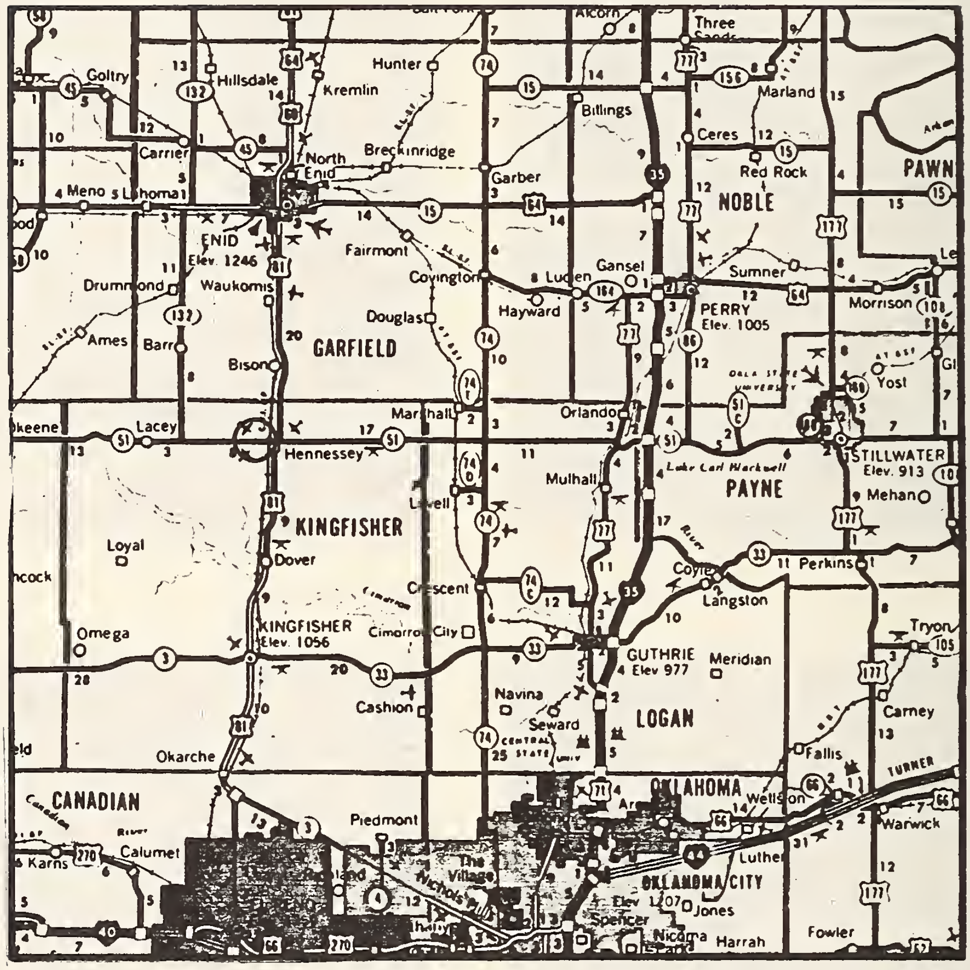
b. Normal to X, ×650 and ×2300

10 μm

SITE Durant, Okla. BORING U-2

SAMPLE No. 2 DEPTH 3.5-4.7 ft

SAMPLING SITE NO. 8, HENNESSEY, OKLA.



Site Location Information

85. Sampling site No. 8 is located in north-central Oklahoma, approximately 1 mile west of Hennessey, Okla. The site is located 0.5 mile west of west junction of U. S. 81 and SH 51 and approximately 1150 ft south of SH 51 on county road (1150 ft south of NE corner of section 23, T19N, R7W).

Site Description

86. Sampling site is located at grade in open gently rolling terrain. Drainage is in a northwesterly direction on a gentle to moderate slope. Surrounding area has a complete grass cover and no trees.

Site Geology

87. Sampling site is located in the Osage Plains Section of the Central Lowlands Physiographic Province. The general topography is flat to gently rolling. Samples were taken from the Hennessey Shale of the Clear Fork Group, Leonardian Series, Permian System. The Hennessey Formation consists of approximately 300 to 900 ft of interbedded red, brown, orange, and blue shales with some calcareous sandstone stringers. The Hennessey shale is underlain by the Garber sandstone (Wichita Group) and overlain by the El Reno Group. The Hennessey Formation which is the time equivalent of the Vale Formation of Texas is exposed throughout north-central Oklahoma and extends to the south and west into Texas.

Sample Description

88. The Hennessey shale sampled is a hard, indurated, relatively unweathered moderate reddish brown (10 R 4/6) noncalcareous, clay stone or clay shale. The disturbed samples lack fissility although there is some indication of bedding. Some small void spaces and occasional fractures are present. The samples exhibit tiny whitish spots consisting of either unoxidized iron, or calcareous or gypsiferous material. The SEM photographs indicate a somewhat massive appearance with moderate particle orientation and wavy stratification.

Description of Climate

89. The climate of Oklahoma is mostly continental in type, as in all of the central Great Plains. Warm, moist air moving northward from the Gulf of Mexico exerts much influence at times, particularly over the southern and more eastern sections of the State where, as a result, humidities and cloudiness are generally greater and precipitation considerably heavier than in the western and northern sections. Summers are long and occasionally very hot. Winters are shorter and less rigorous than those of the more northern Plain States. Periods of extreme cold are infrequent.

90. The mean annual temperature over the State ranges from 64°F along the southern border to about 60°F along the northern border. It then decreases westward across the Panhandle to about 57°F in Cimarron County. Temperatures of 90°F or higher occur, on an average, about

85 days per year in the western Panhandle and in the northeast corner of the State. In the southwest, the average is about 120 days, and in the southeast from 95 to 100 days. Temperatures of 100°F or higher are common over the State from May well into September. In the southwest part of the State the average number of 100°F days is 20 to 25 per year. Other sections of the State will average somewhat less, but very seldom will any location in the State not reach a 100°F temperature sometime during the summer months.

91. Low humidities and good southerly breezes usually accompany the high summer temperatures and somewhat lessen their discomforting effect. Occasionally strong, hot winds accompany the high daytime temperatures; this combination produces rapid evaporation.

92. Temperatures of 32°F or less occur on an average of 55 to 65 days per year along the southern tier of counties and from 90 to 100 days per year along the Kansas border in the north-central and northeastern sections of the State. In the Panhandle, days with 32°F or less occur, on an average, 125 to 140 days per year. The lowest temperature of record is -27°F and was observed at Watts on January 18, 1930, and at Vinita on February 13, 1905.

93. Frozen soil is not a major problem, nor much of a deterrent to seasonal activities. Its occurrence is rather infrequent, of very limited extent, and of brief duration. The average maximum depth that frost penetrates the soil ranges from less than 3 in. in the southeastern corner of the State to more than 10 in. in the extreme northwestern portion. Extreme frost penetration ranges from 10 in. in the southeast corner to about 30 in. in the northwest corner of the Panhandle. Factors having an important bearing on frost penetration are severity and duration of temperature below freezing; condition, character, and moisture content of the soil; and amount and character of protective cover of the soil including snow cover.

94. The geographical distribution of rainfall decreases sharply from east to west. Average annual precipitation ranges from about 56 in. in southern LeFlore County, in the southeastern corner of the State, to 15 in. in the extreme western Panhandle. The greatest annual

precipitation recorded at an official reporting station was 84.47 in. at Kiamichi Tower in southern LeFlore County in 1957. The least annual amount was 6.53 in. at Regnier in northwestern Cimarron County in 1956.

95. Frequency of rainfall, as determined from the average number of days with 0.01 in. or more, varies from 95 to 100 days a year in the extreme east to from 70 to 80 days a year over the western third of the State.

96. Relative humidity averages about 10 percent higher in the eastern portion of the State because of lower elevations and more frequent inflow of Gulf moisture. Summer afternoon and early evening humidities are considerably lower than those of winter.

97. Average annual lake evaporation varies about 48 in. in the extreme eastern sections of the State to as high as 65 in. in the southwestern corner. In the western Panhandle approximately 58 in. of water is evaporated each year. The importance of these evaporative losses from reservoirs and other surface water supplies has prompted a good deal of research to find ways of retarding the evaporation process.

98. Prevailing winds are southerly although northerly winds predominate during the winter months. Average yearly wind speeds vary from 9 mph in the east to approximately 14 mph in the west. March and April are the windiest months, and July and August the calmest.

Climatic Data Summary

Reporting Station: Hennessey 1N (34-4055-05)

Mean Monthly Temperature and Normal
Monthly Precipitation for Period 1941-70:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature, °F	36.7	41.5	48.4	60.5	69.3	78.6	83.2	82.7	74.2	63.5	49.1	39.5	60.6
Precipitation, in.	0.84	1.11	1.67	2.90	4.81	4.22	2.99	2.65	3.18	2.50	1.33	1.16	29.36

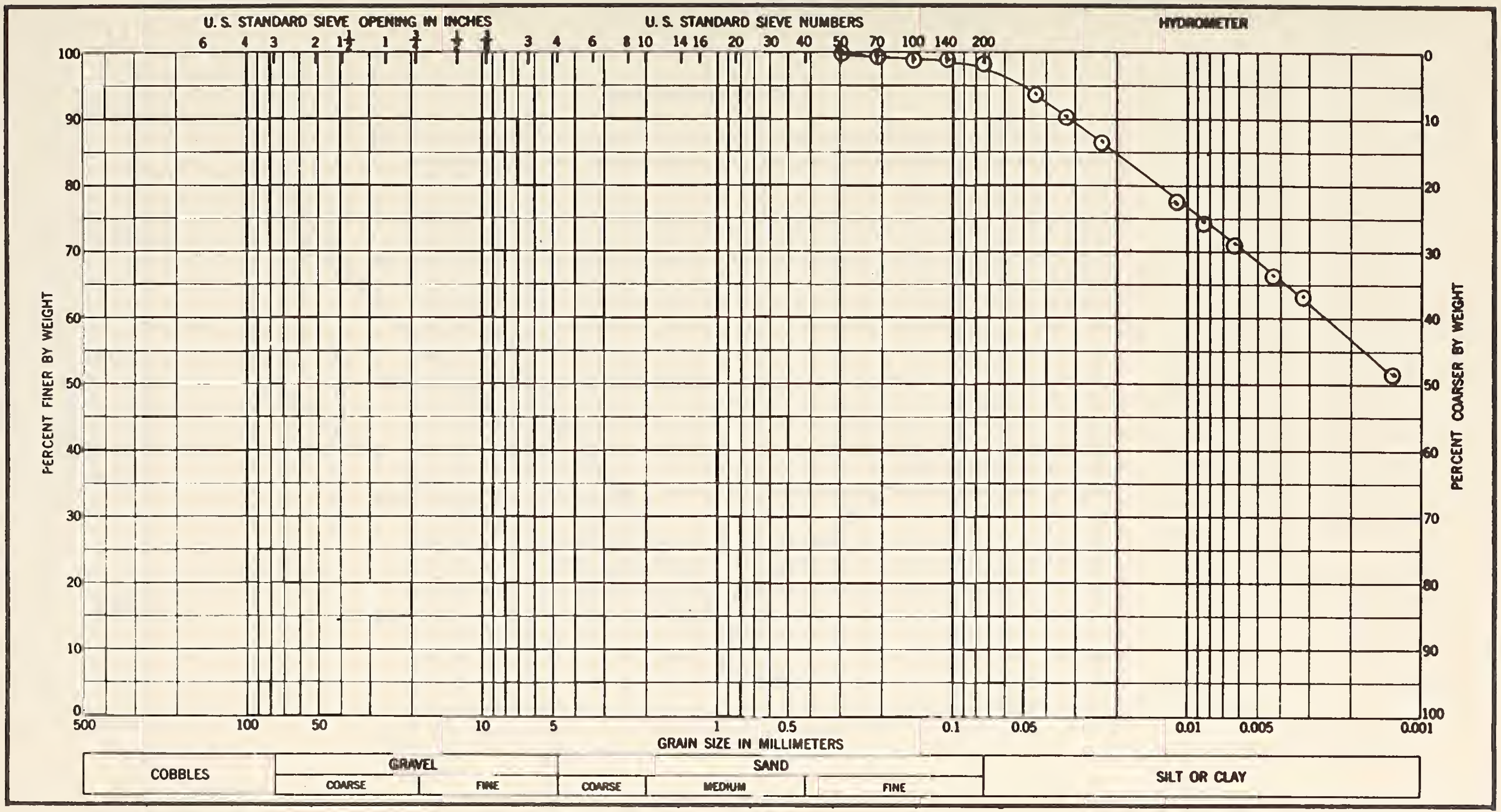
Average Monthly Temperature and
Total Monthly Precipitation for 1971-75:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1971													
Temperature, °F	35.9	--*	--*	62.6	70.2	81.1	84.2	80.5	75.1	64.8	50.6	41.7	--
Precipitation, in.	1.37	1.66	0.00	1.64	1.20	5.97	2.12	0.69	5.28	3.31	1.23	2.22	26.69
1972													
Temperature, °F	35.7	43.4	55.7	65.2	69.1	79.6	81.3	80.9	76.3	--*	43.8	34.1	--
Precipitation, in.	0.07	0.23	0.94	2.03	2.05	2.33	2.05	4.79	2.26	3.51	2.78	1.09	24.13
1973													
Temperature, °F	33.9	39.9	52.2	55.4	68.2	77.2	81.8	82.1	--*	66.3	52.8	39.3	--
Precipitation, in.	2.80	0.58	6.22	2.37	2.47	2.53	3.06	0.23	6.70	2.15	2.48	0.84	32.43
1974													
Temperature, °F	34.4	44.7	54.2	61.8	73.9	76.1	85.1	78.6	64.8	62.6	48.5	39.3	60.3
Precipitation, in.	0.34	3.01	3.02	2.47	4.70	1.24	0.69	9.35	5.70	4.51	5.73	1.55	42.32
1975													
Temperature, °F	39.9	34.1	47.0	59.3	68.4	76.9	80.6	82.2	70.2	--*	50.2	42.1	--
Precipitation, in.	2.63	2.42	2.76	0.72	6.99	8.76	1.28	2.87	2.23	1.43	1.92	0.61	34.62

Thornthwaite Moisture Index:

1970	1971	1972	1973	1974	1975	
-8.19	5.07	-6.87	40.42	17.23	32.67	Avg = 13.39

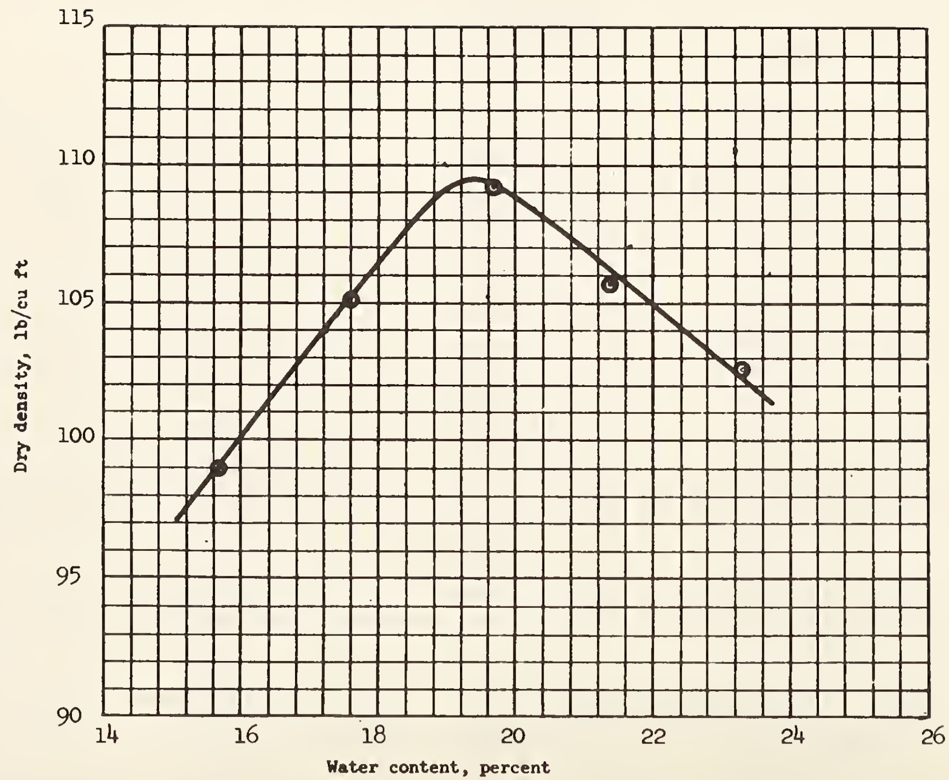
* Record missing.



GRADATION CURVE

SITE Hennessey, Okla. BORING U-1

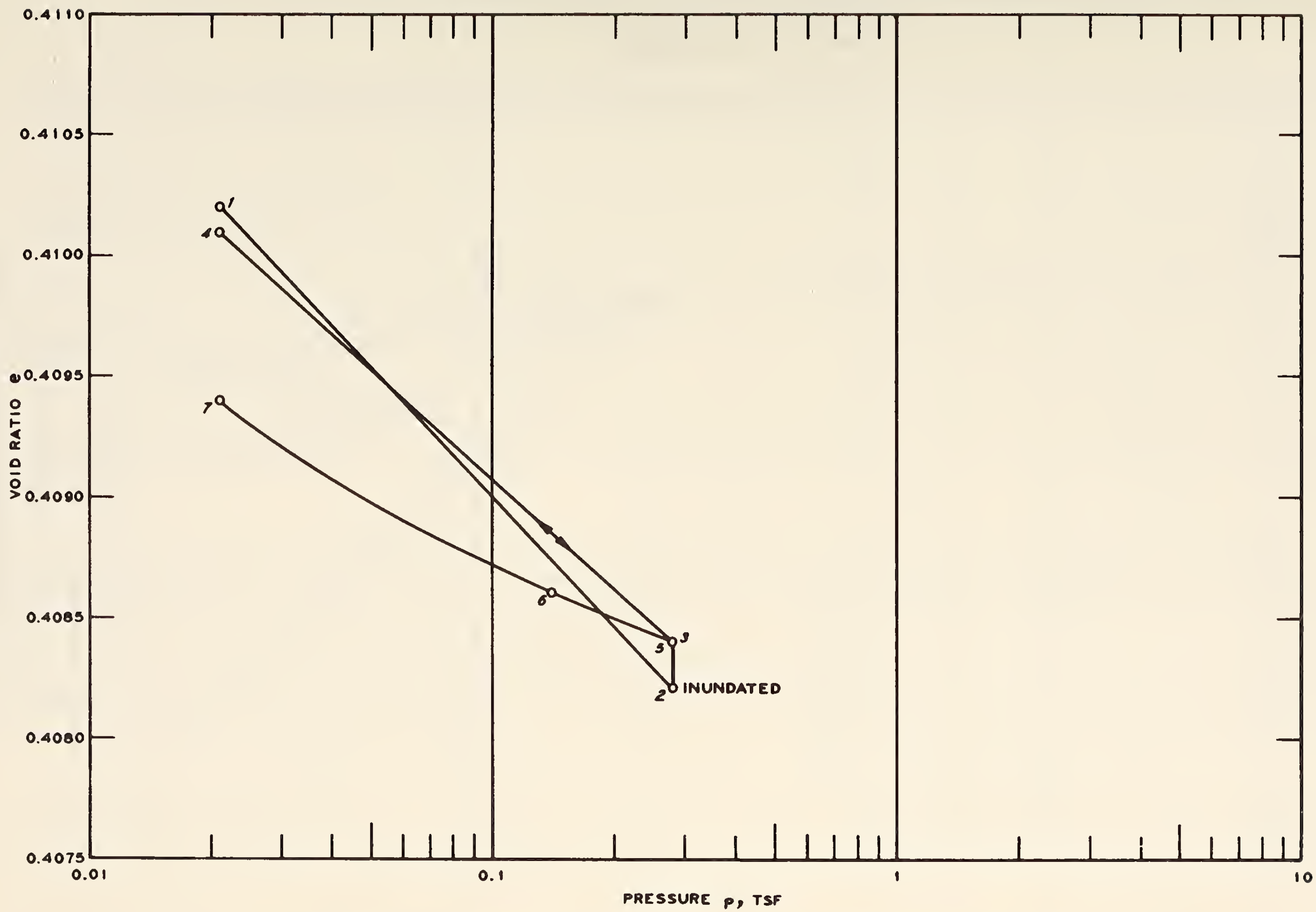
SAMPLE No. 2 DEPTH 3.5-5.6 ft



COMPACTION CURVE

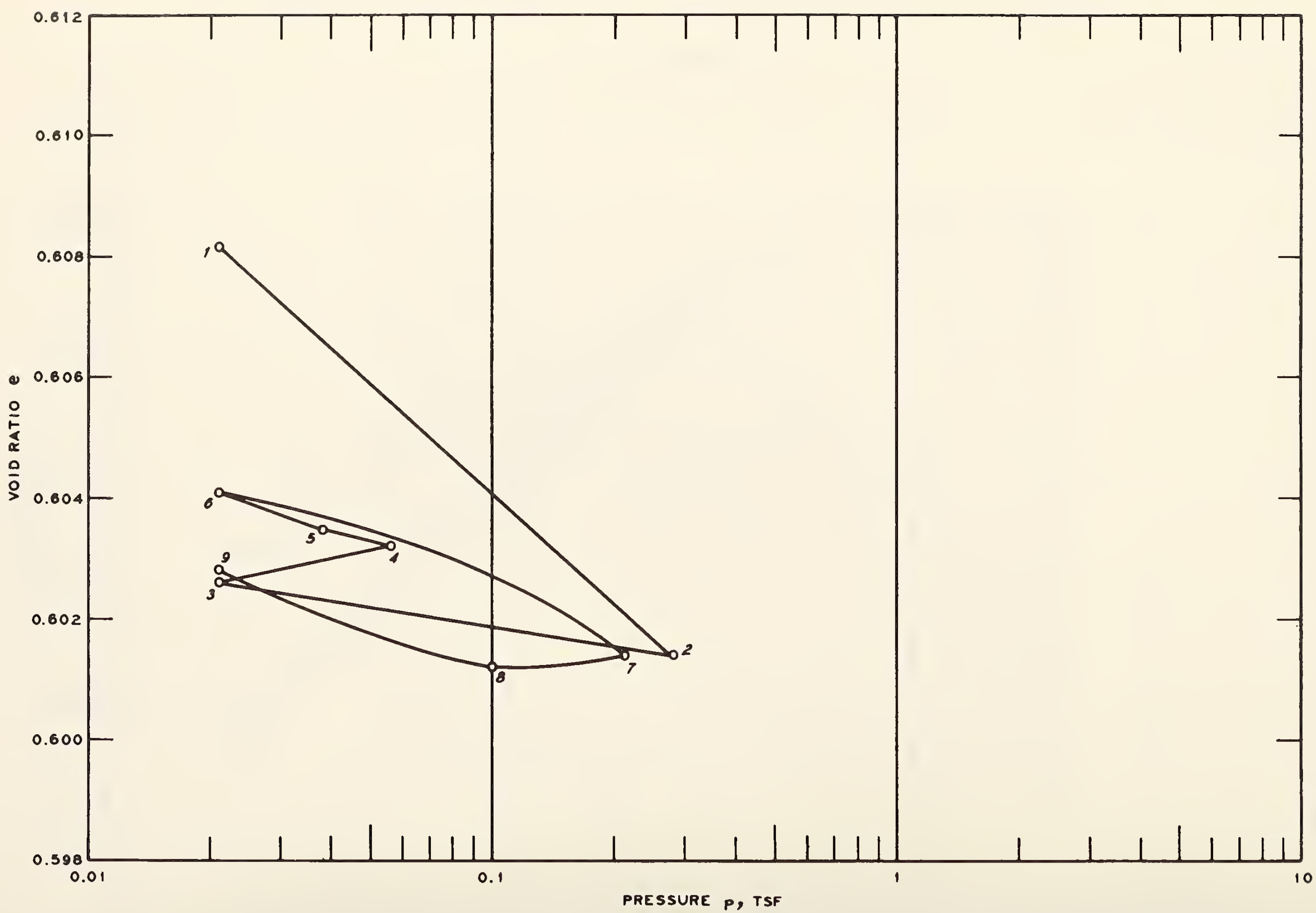
SITE Hennessey, Okla.

SAMPLE Disturbed



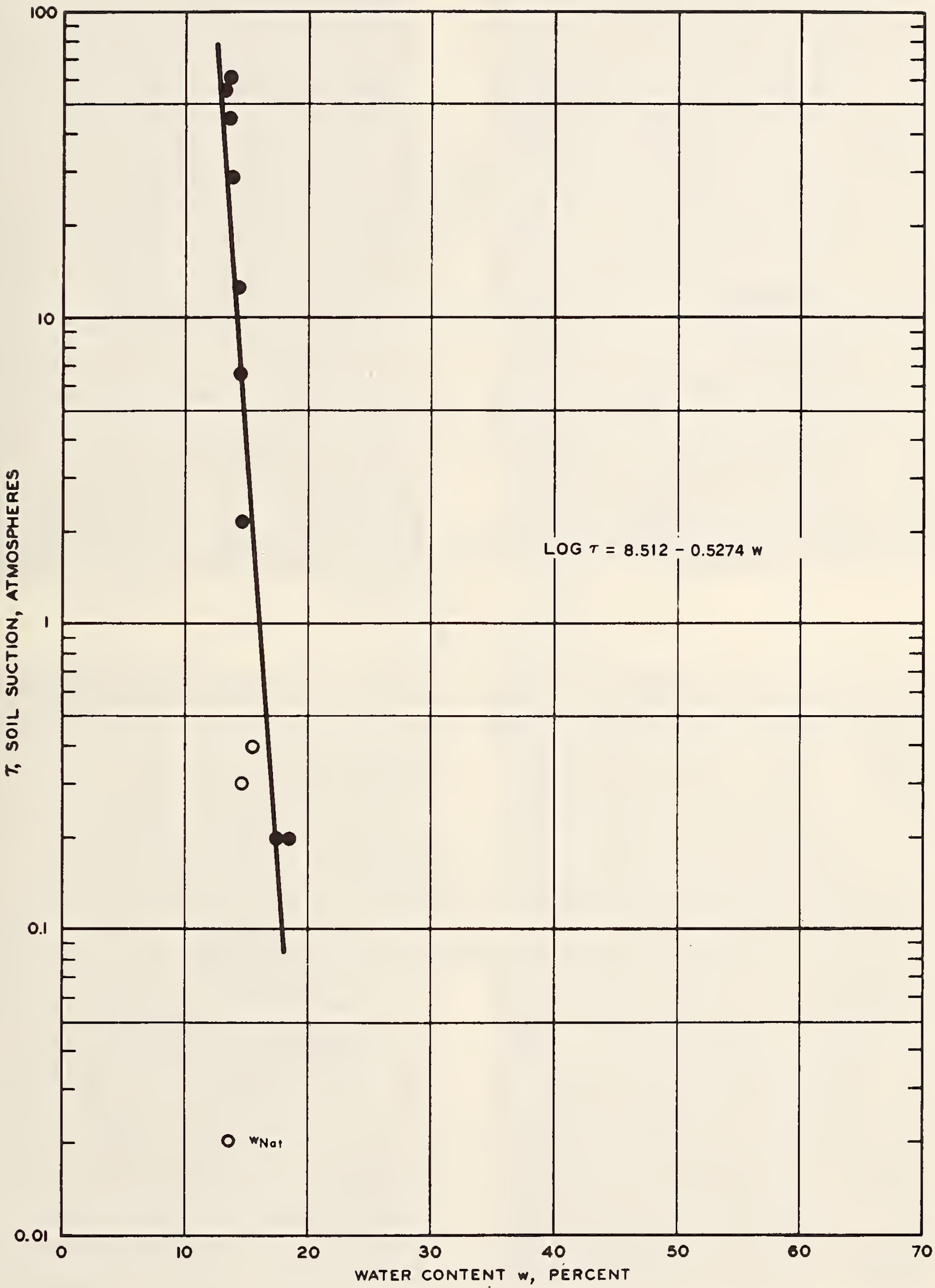
OVERBURDEN SWELL TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

SITE Hennessey, Okla. BORING U-1 SAMPLE No. 2 DEPTH 3.5-4.7 ft



CONSTANT VOLUME SWELL PRESSURE TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

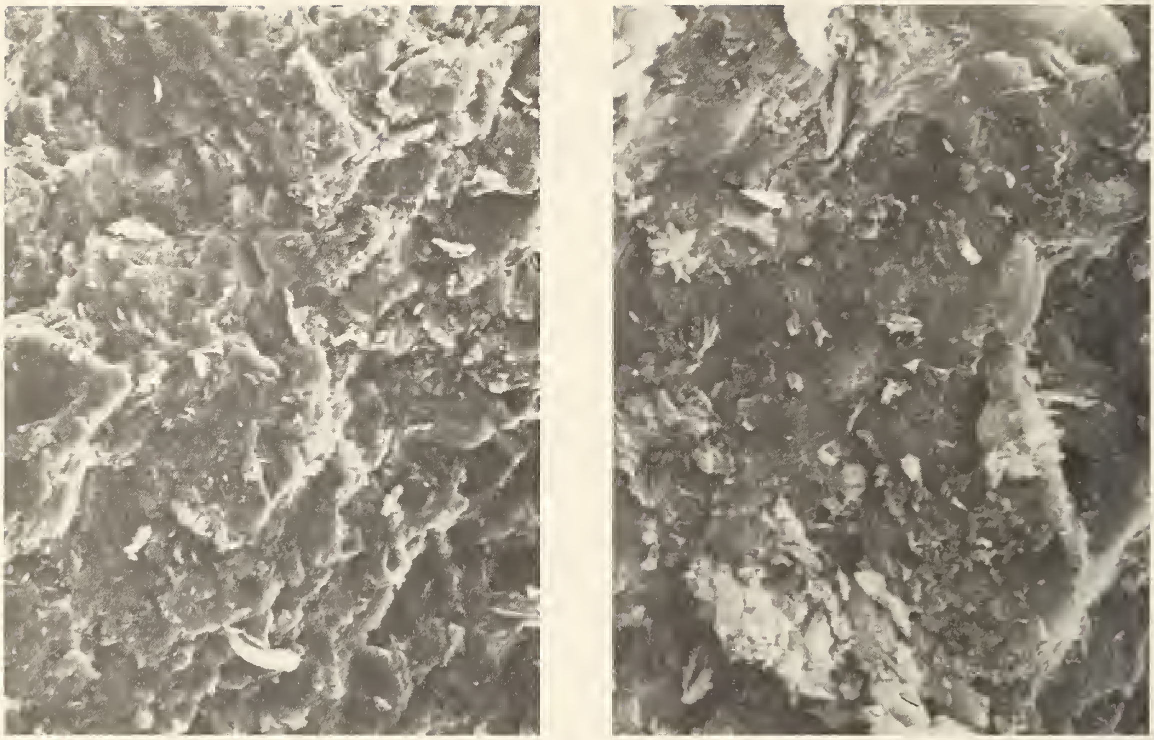
SITE Hennessey, Okla. BORING U-1 SAMPLE No. 2 DEPTH 3.5-5.6 ft



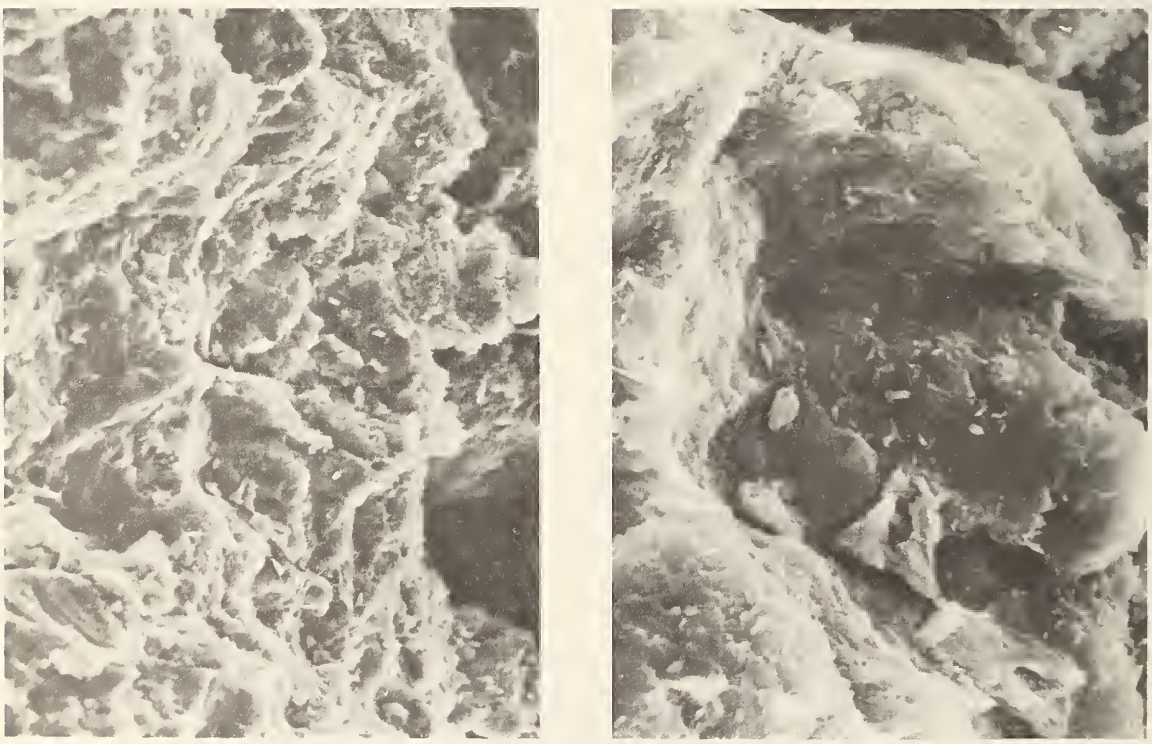
SOIL SUCTION VERSUS WATER CONTENT

SITE Hennessey, Okla. BORING U-1

SAMPLE No. 2 DEPTH 3.5-5.6 ft



a. Normal to Y, ×650 and ×2300



10 μm

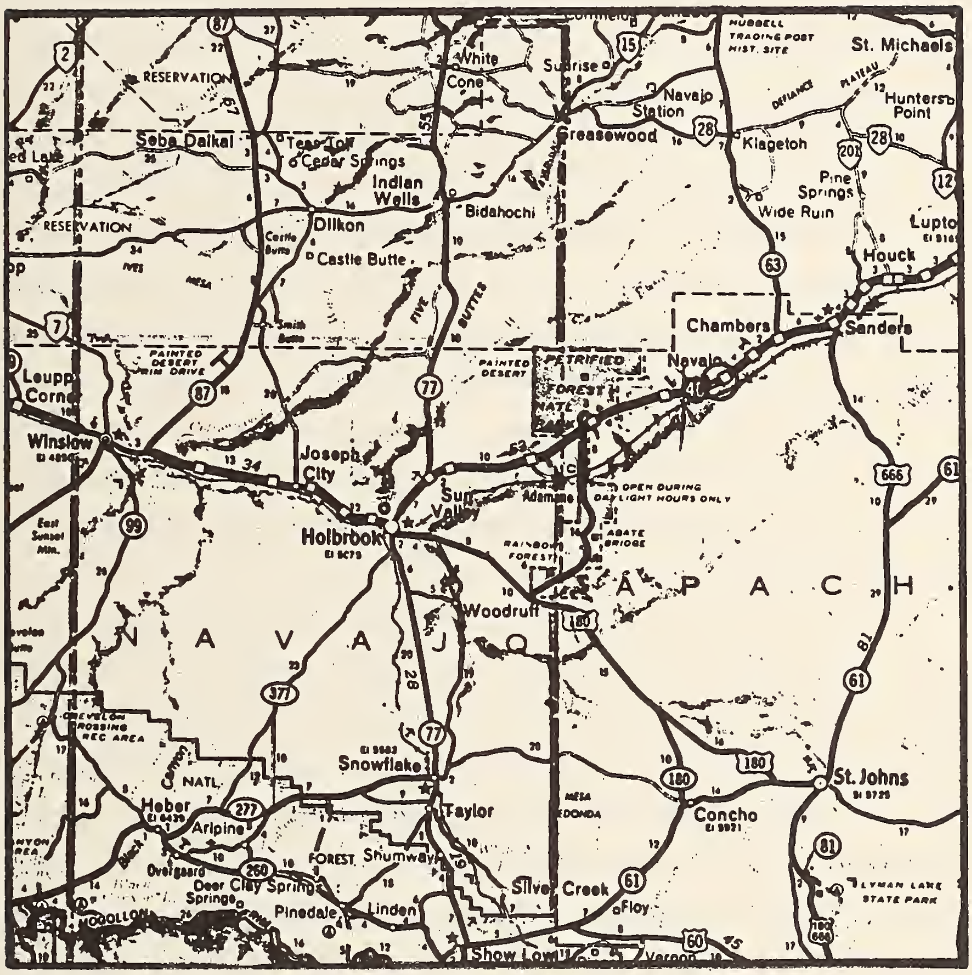
b. Normal to X, ×650 and ×2300

10 μm

SITE Hennessey, Okla. BORING U-1

SAMPLE No. 2 DEPTH 3.5-5.6 ft

SAMPLING SITE NO. 9, HOLBROOK, ARIZ.
(No. 1, I-40)



Site Location Information

99. Sampling site No. 9 is located in east-central Arizona approximately 40 miles northeast of Holbrook, Ariz. The site is located approximately 8 miles west of I-40 and SH 63 junction on I-40; also, 2 miles west of Navajo Interchange. Samples were taken at station 875+50 in the median approximately 60 ft north of centerline of eastbound lane (near milepost 322.77). Approximate description is northwest corner of southwest quarter of section 22, T-20N, R26E.

Site Description

100. Sampling site is located in a cut section (depth varies from zero to $\approx$ 30 ft) in open, gently rolling terrain. Drainage is in a westerly direction on a very gentle slope. Surrounding area has no vegetative cover.

Site Geology

101. Sampling site is located in the Southeastern Navajo Section of the Colorado Plateau Physiographic Province. Samples were taken in the Chinle Formation of the Upper Series of the Triassic System. The Chinle Formation consists of interbedded shaley sandstones and sandy shales and varies in thickness from approximately 600 ft to over 2000 ft. The Chinle overlies the conglomerates of the Shinarump Formation and exhibits a gradational upper contact with the sands of the overlying Wingate Formation. The outcrop area, which is relatively narrow, extends around the Colorado Plateau in northeastern and east-central Arizona.

Sample Description

102. The Chinle Formation as sampled at the I-40 site is a hard, indurated, relatively unweathered, grayish red (10 R 4/2) siltstone. Well-developed stratification is not apparent in most samples; however, some samples exhibit some small-scale cross bedding as indicated by the presence of nonparallel whitish laminations. The whitish laminations and some white circular areas are calcareous. Void spaces are not common, but fractures are present in limited amounts. Mica is a relatively common accessory mineral. The SEM photographs indicate moderate particle orientation with wavy stratifications. Photos show some microfractures.

Description of Climate

103. Arizona covers 113,909 square miles, with about 350 square miles of water surface. The State can be divided into three main topographical areas: (a) the northeastern portion is a high plateau averaging between 5,000 and 7,000 ft in elevation; (b) running diagonally from the southeastern to the northwestern corners of the State is a mountainous region with maximum elevations between about 9,000 and 12,000 ft above sea level; and (c) the southwestern third of the State

is made up of low mountain ranges and desert valleys.

104. The higher elevations of the State, running diagonally from the southeast to the northwest, average between 25 and 30 in. of precipitation (rain plus melted snow) annually, while the desert southwest has averages as low as 3 or 4 in. per year. The desert valleys of southwestern Arizona are an extension of the Sonora Desert of Mexico, with elevations as low as about 100 ft above sea level in the lower Colorado River Valley. The plateau country in the northeastern corner of the State receives approximately 10 in. of precipitation annually.

105. Great extremes occur between day and night temperatures throughout Arizona. The daily range between maximum and minimum temperatures sometimes runs as high as 50 to 60°F during drier portions of the year. During winter months, daytime temperatures may average 70°F, with night temperatures often falling to freezing or slightly below in lower desert valleys. In the summer the pine-clad forests in the central part of the State may have afternoon temperatures of 80°F, while night temperatures drop to 35 to 40°F.

106. Precipitation throughout Arizona is governed to a great extent by elevation and the season of the year. From November through March, storm systems from the Pacific Ocean cross the State. These winter storms occur frequently in the higher mountains of the central and northern parts of the State and sometimes bring with them heavy snows. Snow accumulation may reach depths of 100 in. or more during the winter. The gradual melting of this snow during the spring serves to maintain a supply of water in the main rivers of the State. Reservoirs on these streams supply water to the desert areas in the lower Salt River Valley and the lower Gila River Valley areas, which are extensively farmed.

107. Summer rainfall begins early in July and usually extends to mid-September. Moisture-bearing winds sweep into Arizona from the southeast, with their source region in the Gulf of Mexico. Summer rains occur in the form of thundershowers which are caused, to a great extent, by excessive heating of the ground and the lifting of moisture-laden air along main mountain ranges. Thus, the heaviest thundershowers are

usually found in mountainous regions of the central and southeastern portions of Arizona. These thunderstorms are often accompanied by strong winds and brief periods of blowing dust prior to the onset of rain. Hail occurs rather infrequently.

108. The average number of days with measurable precipitation per year varies from 72 in. in the Flagstaff region to 34 at Phoenix, 50 in Tucson, 53 at Winslow, and 15 at Yuma. A large portion of Arizona is included in the semiarid region of the United States. Long periods often occur with little or no precipitation. The air is generally dry and clear, with relatively low humidity and a high percentage of sunshine. April, May, and June are the months with the greatest number of clear days, while July and August, as well as December, January, and February have the cloudiest weather and lowest percent of sunshine. Humidities, while low when compared to most other states, are higher throughout much of Arizona during July and August, which is the thunderstorm season. Annual average humidity values, based on four readings per day, show Flagstaff with 55 percent; Phoenix, 38 percent; Tucson, 38 percent; Winslow, 46 percent; and Yuma, 33 percent. Yearly averages of percent of possible sunshine show Phoenix with 86 percent; Tucson, 86 percent; and Yuma, 92 percent. Due to high temperatures, the dryness of the air, and the high percentage of sunshine, evaporation rates in Arizona are high. Mean annual lake evaporation varies from about 80 in. in the southwestern corner of the State to about 50 in. in the northeastern corner. Phoenix averages about 72 in. and Tucson 70 in. per year.

Climatic Data Summary

Reporting Station: Petrified Forest National Park (02-6468-02)

Mean Monthly Temperature and Normal
Monthly Precipitation for Period 1941-70:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature, °F	34.1	39.1	44.1	52.7	61.2	70.3	76.4	74.2	68.2	56.8	43.6	35.1	54.7
Precipitation, in.	0.44	0.45	0.53	0.35	0.32	0.35	1.39	1.89	1.05	0.92	0.51	0.49	8.69

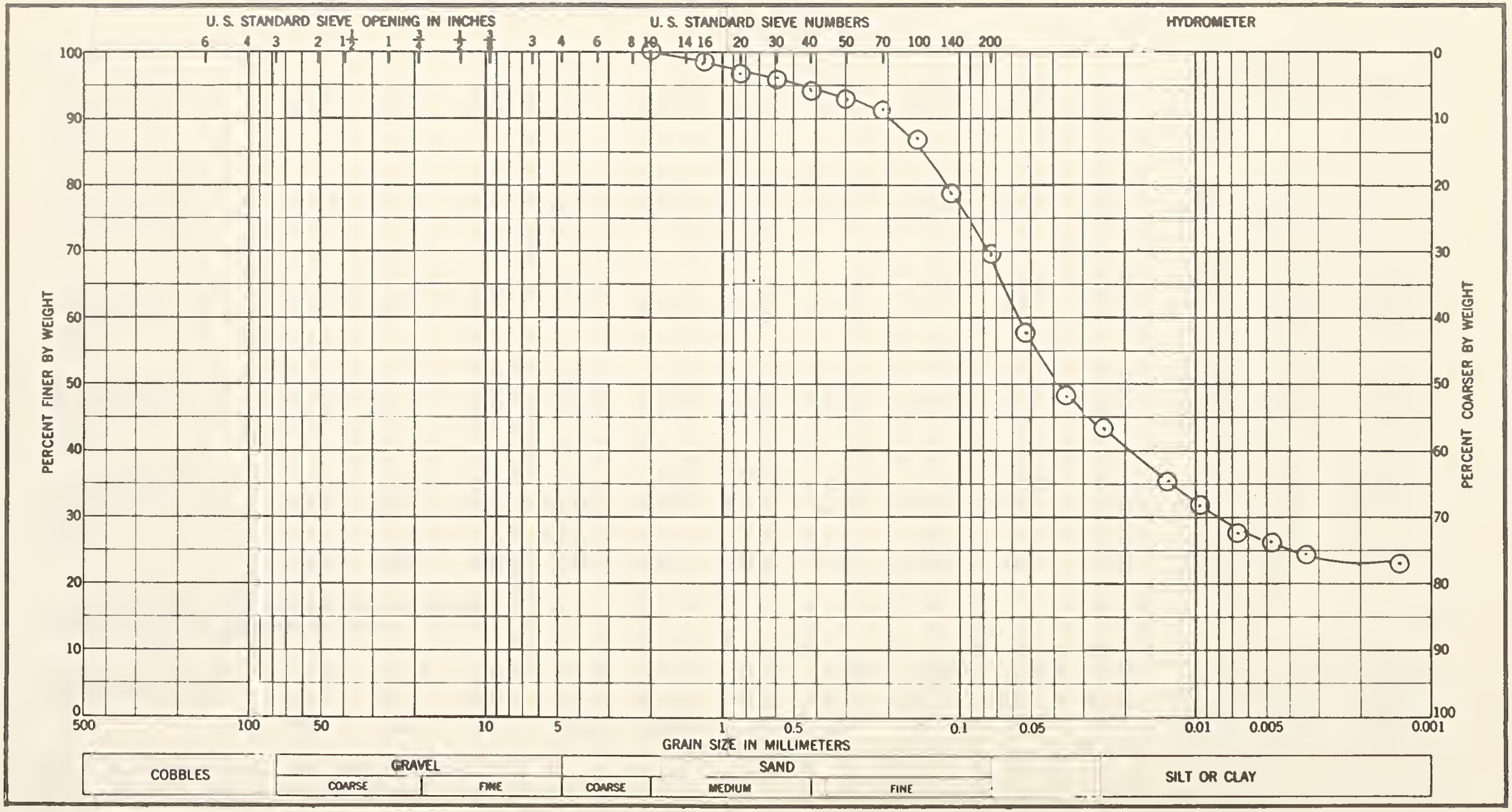
Average Monthly Temperature and
Total Monthly Precipitation for 1971-75:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1971													
Temperature, °F	32.1	36.8	44.6	50.5	56.9	69.8	77.8	74.0	65.9	51.9	43.0	32.8	53.0
Precipitation, in.	0.17	0.15	0.00	0.49	0.00	0.00	0.78	1.16	3.07	1.60	0.30	0.63	8.35
1972													
Temperature, °F	36.3	41.1	50.1	53.5	59.5	68.8	76.8	73.7	67.6	56.2	39.5	33.8	54.7
Precipitation, in.	0.00	0.00	0.00	0.00	1.13	0.72	0.44	0.82	0.54	3.95	0.64	0.45	8.69
1973													
Temperature, °F	31.7	38.6	41.0	47.9	60.6	69.5	75.6	74.1	66.1	56.5	45.2	36.2	53.6
Precipitation, in.	0.21	1.41	0.83	1.29	1.77	0.58	0.29	1.13	0.01	0.05	0.81	0.00	8.38
1974													
Temperature, °F	33.8	36.4	48.3	51.3	63.7	75.0	74.7	73.2	66.8	56.9	42.6	32.2	54.6
Precipitation, in.	1.00	0.04	0.29	0.00	0.00	0.00	1.43	2.03	0.34	3.07	0.07	0.05	8.32
1975													
Temperature, °F	30.8	36.4	42.8	47.3	57.1	68.0	75.2	74.0	66.5	56.0	41.6	31.8	52.3
Precipitation, in.	0.31	0.80	0.90	0.45	0.38	0.02	1.20	0.62	2.36	0.00	0.44	0.56	8.04

Thornthwaite Moisture Index:

1970	1971	1972	1973	1974	1975
-25.78	-30.72	-22.62	5.58	-29.99	-15.17

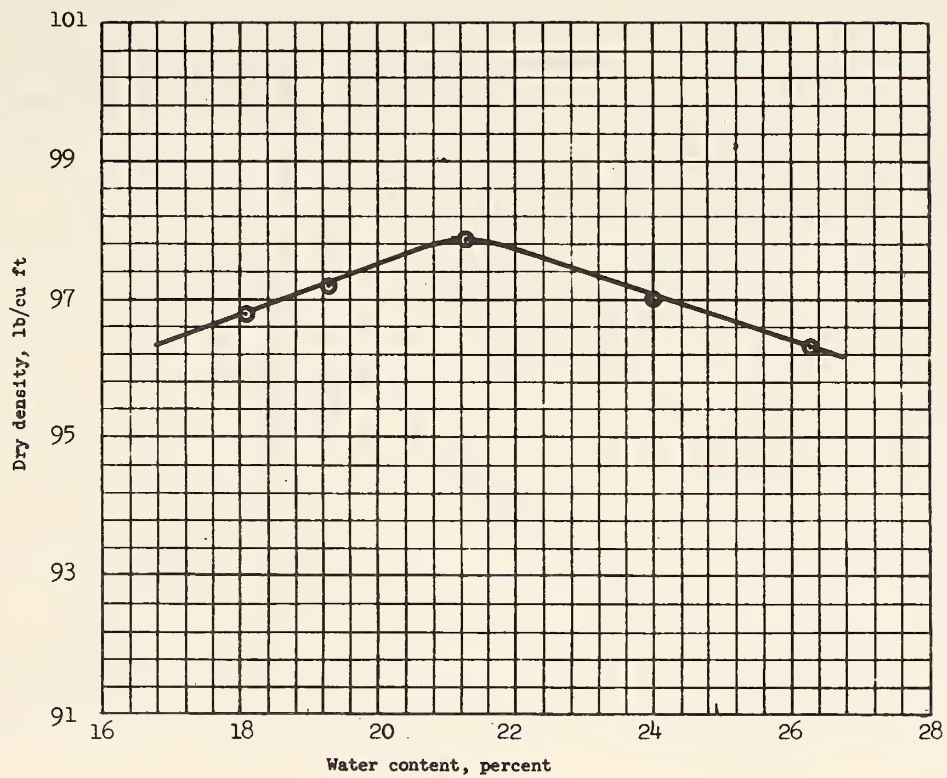
Avg = -19.78



GRADATION CURVE

SITE Holbrook, Ariz. (No. 1, I-40) BORING U-2

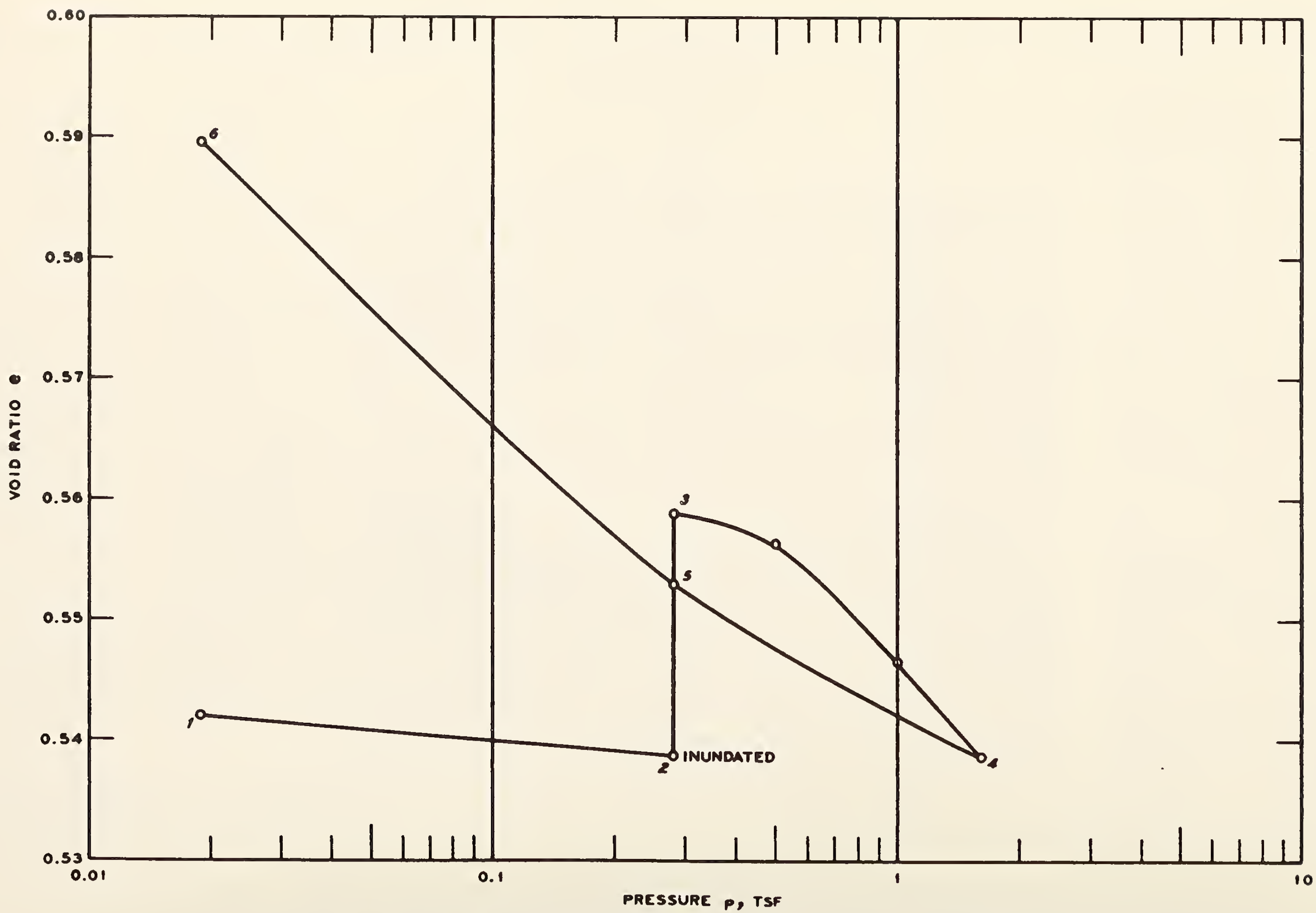
SAMPLE No. 1 DEPTH 2.5-4.2 ft



COMPACTION CURVE

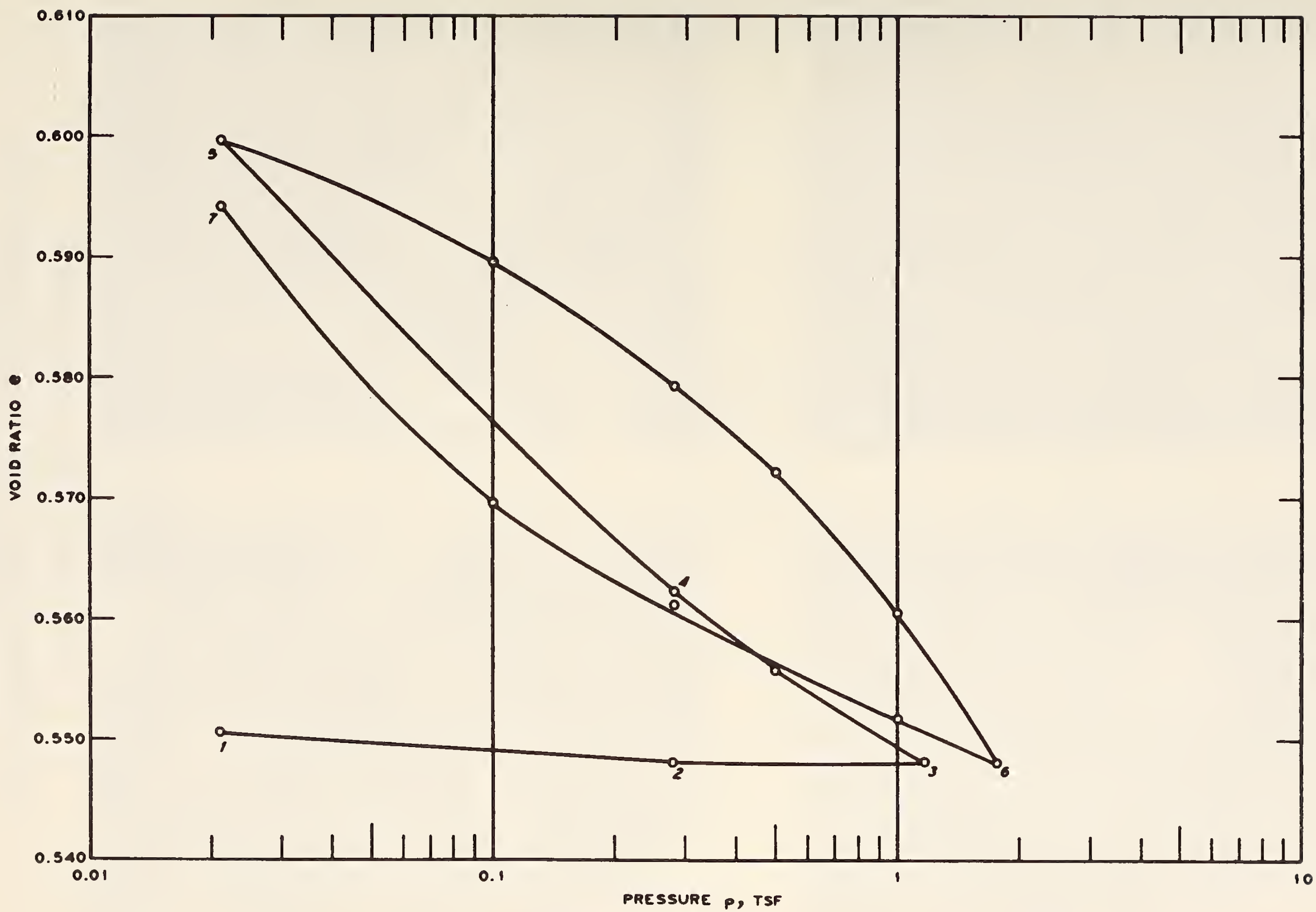
SITE Holbrook, Ariz. (No. 1, I-40)

SAMPLE Disturbed



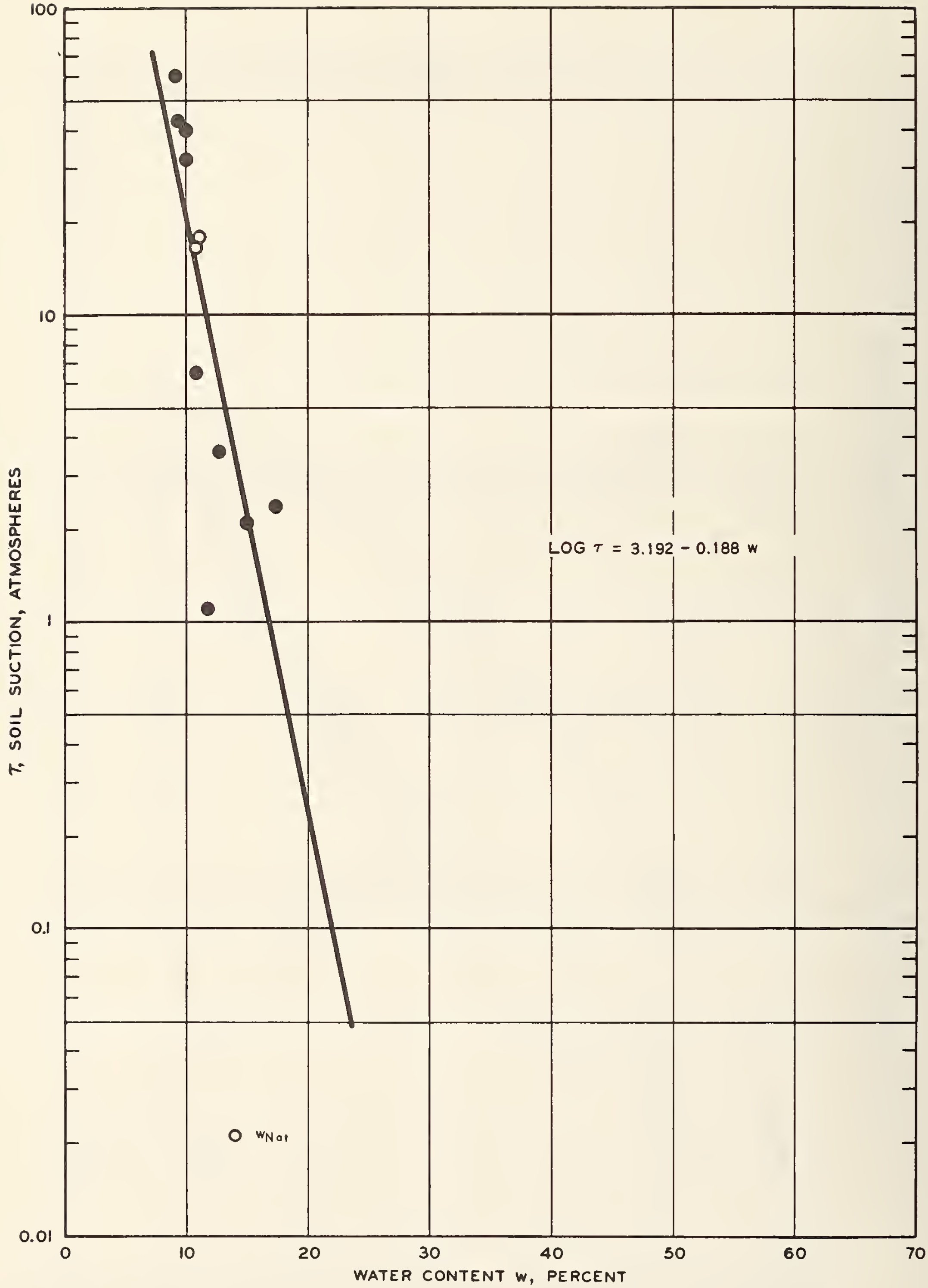
OVERBURDEN SWELL TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

SITE Holbrook, Ariz. (No. 1, I-40) BORING U-2 SAMPLE No. 1 DEPTH 2.5-4.2 ft



CONSTANT VOLUME SWELL PRESSURE TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

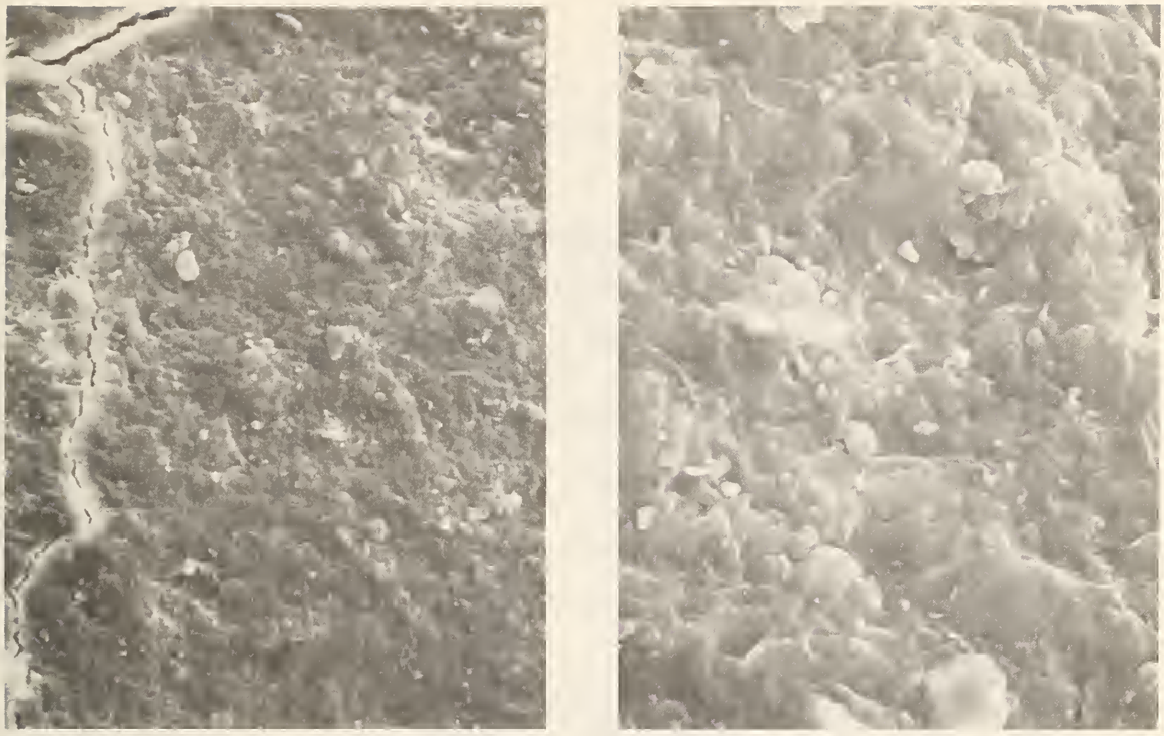
SITE Holbrook, Ariz. (No. 1, I-40) BORING U-2 SAMPLE No. 1 DEPTH 2.5-4.2 ft



SOIL SUCTION VERSUS WATER CONTENT

SITE Holbrook, Ariz. (No. 1, I-40) BORING U-2

SAMPLE No. 1 DEPTH 2.5-4.2 ft



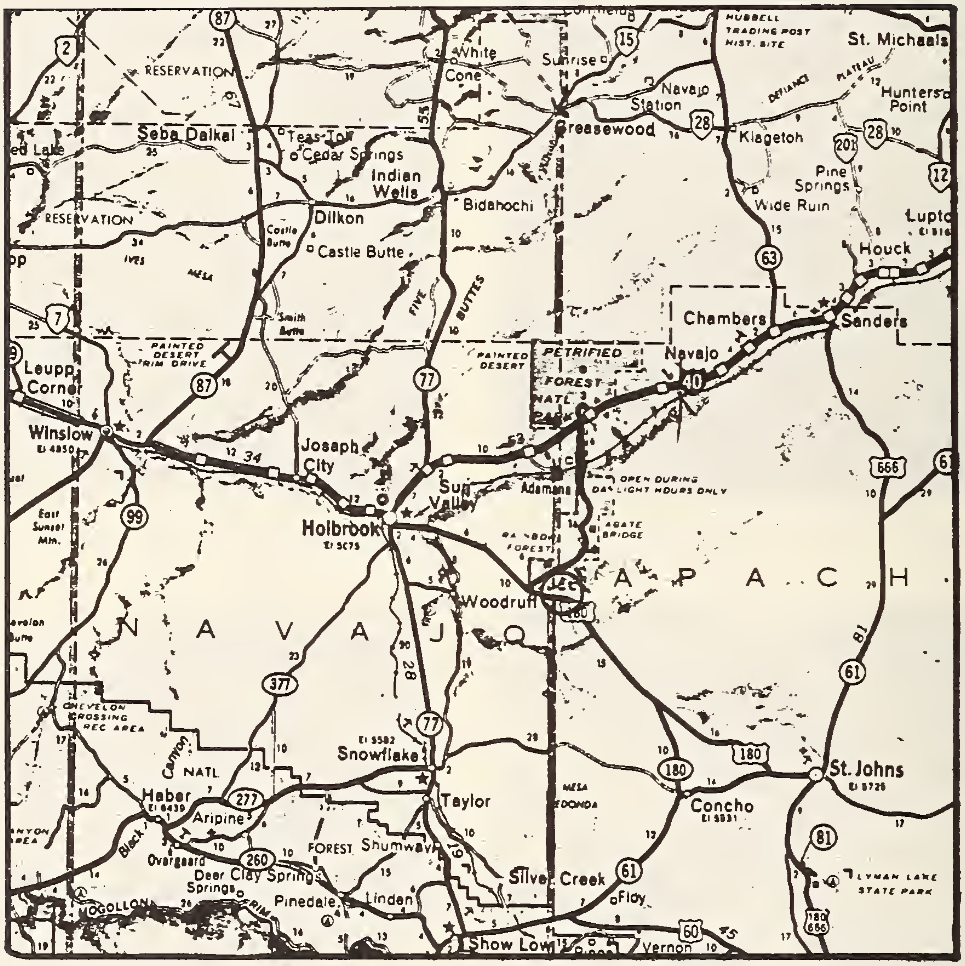
a. Normal to Y, ×650 and ×2300

b. Normal to X, ×650 and ×2300

SITE Holbrook, Ariz. (No. 1, I-40) BORING U-2

SAMPLE No. 1 DEPTH 2.5-4.2 ft

SAMPLING SITE NO. 10, HOLBROOK, ARIZ.
(No. 2, SH 180)



Site Location Information

109. Sampling site No. 10 is located in east-central Arizona approximately 25 miles southeast of Holbrook, Ariz. The site is located on U. S. 180 near county line between Apache and Navajo counties. The site is approximately 4 miles east of junction of U. S. 180 and Petrified Forest National Park road. Samples were taken at station 857+50 in the right-of-way approximately 50 ft south of centerline (near milepost 323.34).

Site Description

110. Sampling site is located in a cut section (depth varies from zero to $\approx$ 7 ft) in open, gently rolling terrain. Drainage is in a southerly direction on a gentle slope (ditches at site are paved). Surrounding area has a sparse grass cover and no trees.

Site Geology

111. Sampling site is located in the Southeastern Navajo Section of the Colorado Plateau Physiographic Province. Samples were taken in the Chinle Formation of the Upper Series of the Triassic System. The Chinle Formation consists of interbedded shaley sandstones and sandy shales and varies in thickness from approximately 600 ft to over 2000 ft. The Chinle overlies the conglomerates of the Shinarump Formation and exhibits a gradational upper contact with the sands of the overlying Wingate Formation. The outcrop area, which is relatively narrow, extends around the Colorado Plateau in northeastern and east-central Arizona.

Sample Description

112. The Chinle Formation as sampled at the SH 180 site is a hard, weakly indurated, moderately weathered, very light gray (N8), to medium dark gray (N4), blocky clay stone exhibiting indistinct bedding. The more weathered fragments are usually lighter in color and calcareous while the material in general is noncalcareous. Fresh specimens exhibit a conchoidal fracture pattern. Some larger fragments (>2 cm) are cut by sinuous fractures. Void spaces along fractures are locally coated with iron oxide or a calcite. The SEM photographs indicate agglomerates or domains of particles in which face-to-face orientation of particles probably exist. Appreciable void space is exhibited in the domains.

Description of Climate

113. Arizona covers 113,909 square miles, with about 350 square miles of water surface. The State can be divided into three main topographical areas: (a) the northeastern portion is a high plateau averaging between 5,000 and 7,000 ft in elevation; (b) running diagonally from the southeastern to the northwestern corners of the State is a

mountainous region with maximum elevations between about 9,000 and 12,000 ft above sea level; and (c) the southwestern third of the State is made up of low mountain ranges and desert valleys.

114. The higher elevations of the State, running diagonally from the southeast to the northwest, average between 25 and 30 in. of precipitation (rain plus melted snow) annually, while the desert southwest has averages as low as 3 or 4 in. per year. The desert valleys of southwestern Arizona are an extension of the Sonora Desert of Mexico, with elevations as low as about 100 ft above sea level in the lower Colorado River Valley. The plateau country in the northeastern corner of the State receives approximately 10 in. of precipitation annually.

115. Great extremes occur between day and night temperatures throughout Arizona. The daily range between maximum and minimum temperatures sometimes runs as high as 50 to 60°F during drier portions of the year. During winter months, daytime temperatures may average 70°F, with night temperatures often falling to freezing or slightly below in lower desert valleys. In the summer the pine-clad forests in the central part of the State may have afternoon temperatures of 80°F, while night temperatures drop to 35 to 40°F.

116. Precipitation throughout Arizona is governed to a great extent by elevation and the season of the year. From November through March, storm systems from the Pacific Ocean cross the State. These winter storms occur frequently in the higher mountains of the central and northern parts of the State and sometimes bring with them heavy snows. Snow accumulation may reach depths of 100 in. or more during the winter. The gradual melting of this snow during the spring serves to maintain a supply of water in the main rivers of the State. Reservoirs on these streams supply water to the desert areas in the lower Salt River Valley and the lower Gila River Valley areas, which are extensively farmed.

117. Summer rainfall begins early in July and usually extends to mid-September. Moisture-bearing winds sweep into Arizona from the southeast, with their source region in the Gulf of Mexico. Summer rains occur in the form of thundershowers which are caused, to a great extent,

by excessive heating of the ground and the lifting of moisture-laden air along main mountain ranges. Thus, the heaviest thundershowers are usually found in mountainous regions of the central and southeastern portions of Arizona. These thunderstorms are often accompanied by strong winds and brief periods of blowing dust prior to the onset of rain. Hail occurs rather infrequently.

118. The average number of days with measurable precipitation per year varies from 72 in. in the Flagstaff region to 34 at Phoenix, 50 in Tucson, 53 at Winslow, and 15 at Yuma. A large portion of Arizona is included in the semiarid region of the United States. Long periods often occur with little or no precipitation. The air is generally dry and clear, with relatively low humidity and a high percentage of sunshine. April, May, and June are the months with the greatest number of clear days, while July and August, as well as December, January, and February have the cloudiest weather and lowest percent of sunshine. Humidities, while low when compared to most other states, are higher throughout much of Arizona during July and August, which is the thunderstorm season. Annual average humidity values, based on four readings per day, show Flagstaff with 55 percent; Phoenix, 38 percent; Tucson, 38 percent; Winslow, 46 percent; and Yuma, 33 percent. Yearly averages of percent of possible sunshine show Phoenix with 86 percent; Tucson, 86 percent; and Yuma, 92 percent. Due to high temperatures, the dryness of the air, and the high percentage of sunshine, evaporation rates in Arizona are high. Mean annual lake evaporation varies from about 80 in. in the southwestern corner of the State to about 50 in. in the northeastern corner. Phoenix averages about 72 in. and Tucson 70 in. per year.

Climatic Data Summary

Reporting Station: Petrified Forest National Park (02-6468-02)

Mean Monthly Temperature and Normal
Monthly Precipitation for Period 1941-70:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature, °F	34.1	39.1	44.1	52.7	61.2	70.3	76.4	74.2	68.2	56.8	43.6	35.1	54.7
Precipitation, in.	0.44	0.45	0.53	0.35	0.32	0.35	1.39	1.89	1.05	0.92	0.51	0.49	8.69

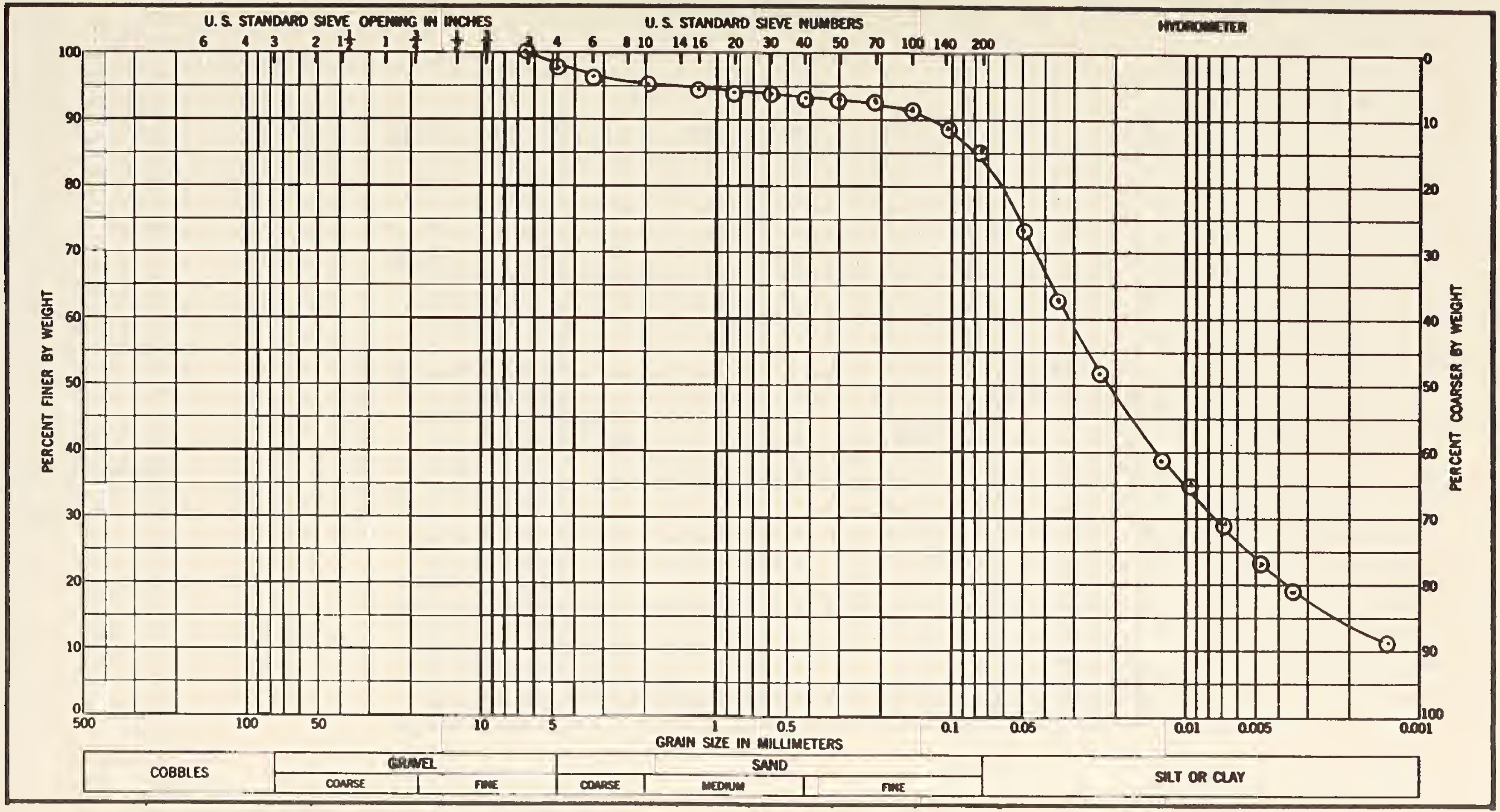
Average Monthly Temperature and
Total Monthly Precipitation for 1971-75:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1971													
Temperature, °F	32.1	36.8	44.6	50.5	56.9	69.8	77.8	74.0	65.9	51.9	43.0	32.8	53.0
Precipitation, in.	0.17	0.15	0.00	0.49	0.00	0.00	0.78	1.16	3.07	1.60	0.30	0.63	8.35
1972													
Temperature, °F	36.3	41.1	50.1	53.5	59.5	68.8	76.8	73.7	67.6	56.2	39.5	33.8	54.7
Precipitation, in.	0.00	0.00	0.00	0.00	1.13	0.72	0.44	0.82	0.54	3.95	0.64	0.45	8.69
1973													
Temperature, °F	31.7	38.6	41.0	47.9	60.6	69.5	75.6	74.1	66.1	56.5	45.2	36.2	53.6
Precipitation, in.	0.21	1.41	0.83	1.29	1.77	0.58	0.29	1.13	0.01	0.05	0.81	0.00	8.38
1974													
Temperature, °F	33.8	36.4	48.3	51.3	63.7	75.0	74.7	73.2	66.8	56.9	42.6	32.2	54.6
Precipitation, in.	1.00	0.04	0.29	0.00	0.00	0.00	1.43	2.03	0.34	3.07	0.07	0.05	8.32
1975													
Temperature, °F	30.8	36.4	42.8	47.3	57.1	68.0	75.2	74.0	66.5	56.0	41.6	31.8	52.3
Precipitation, in.	0.31	0.80	0.90	0.45	0.38	0.02	1.20	0.62	2.36	0.00	0.44	0.56	8.04

Thornthwaite Moisture Index:

1970	1971	1972	1973	1974	1975
-25.78	-30.72	-22.62	5.58	-29.99	-15.17

Avg = -19.78



GRADATION CURVE

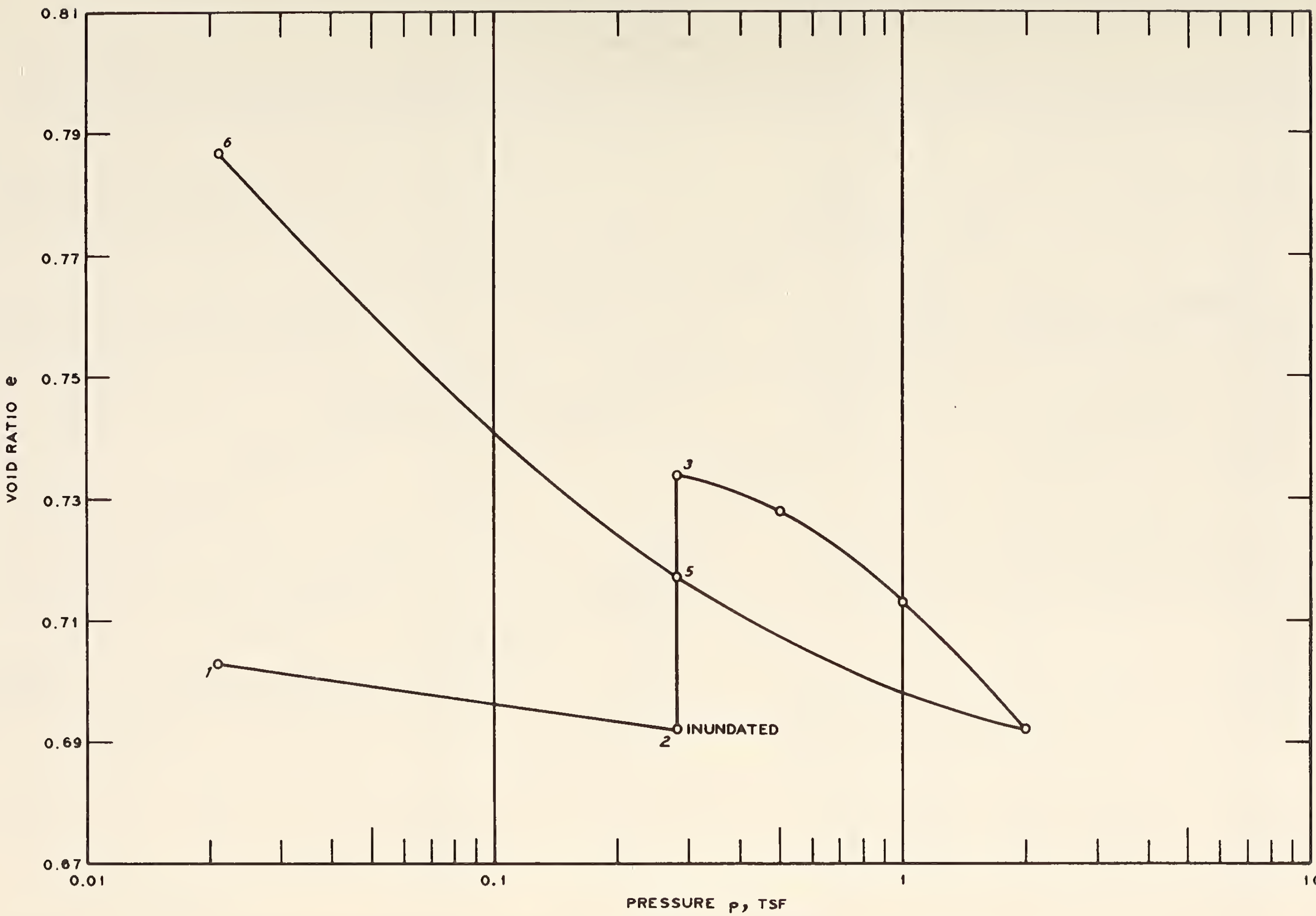
SITE Holbrook, Ariz. (No. 2, SH 180) BORING U-2

SAMPLE No. 1 DEPTH 2.0-4.3 ft

COMPACTION CURVE

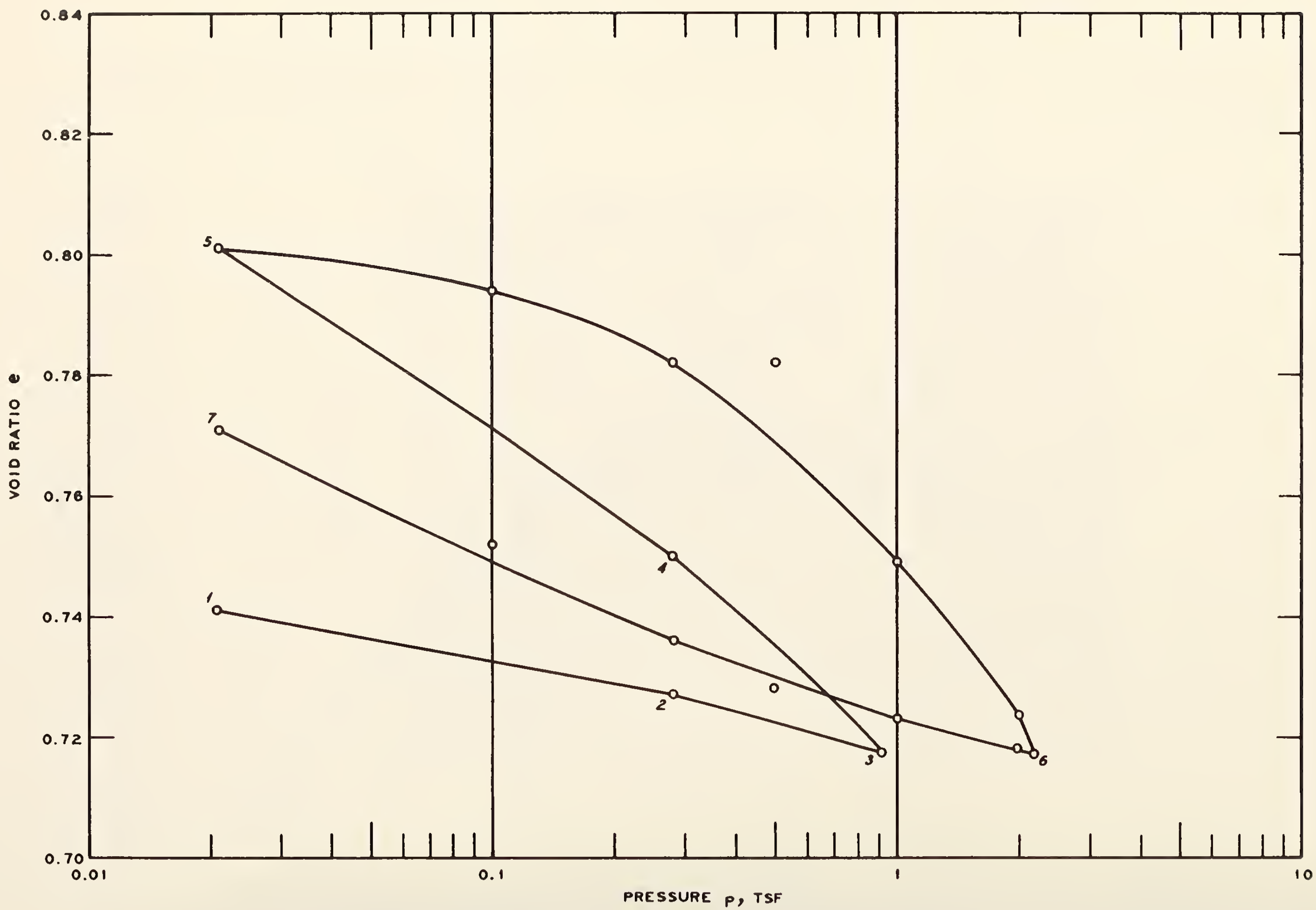
SITE Holbrook, Ariz. (No. 2, SH 180)

SAMPLE Disturbed



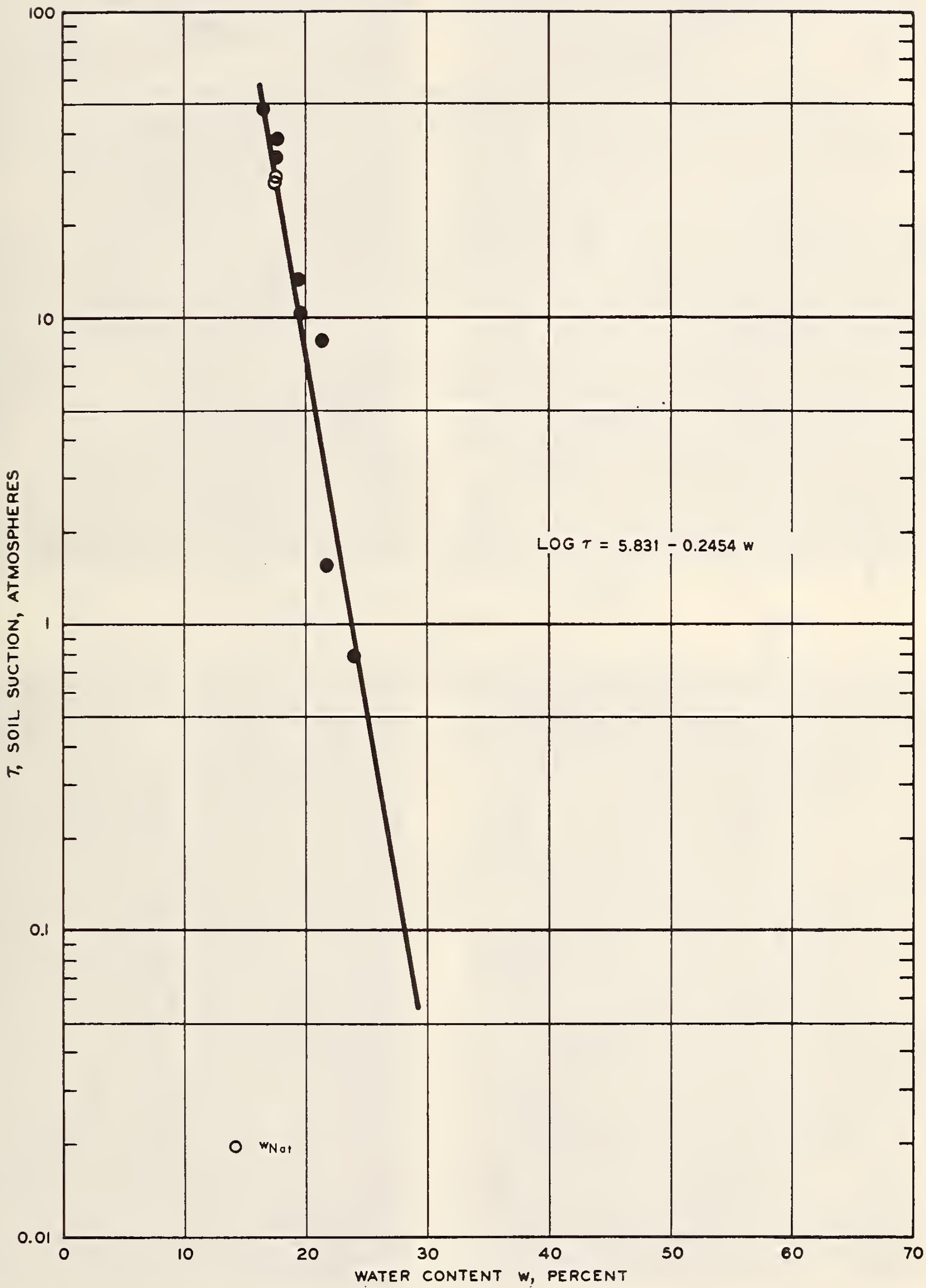
OVERBURDEN SWELL TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

Site Holbrook, Ariz. (No. 2, SH 180) BORING U-2 SAMPLE No. 1 DEPTH 2.0-4.3 ft



CONSTANT VOLUME SWELL PRESSURE TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

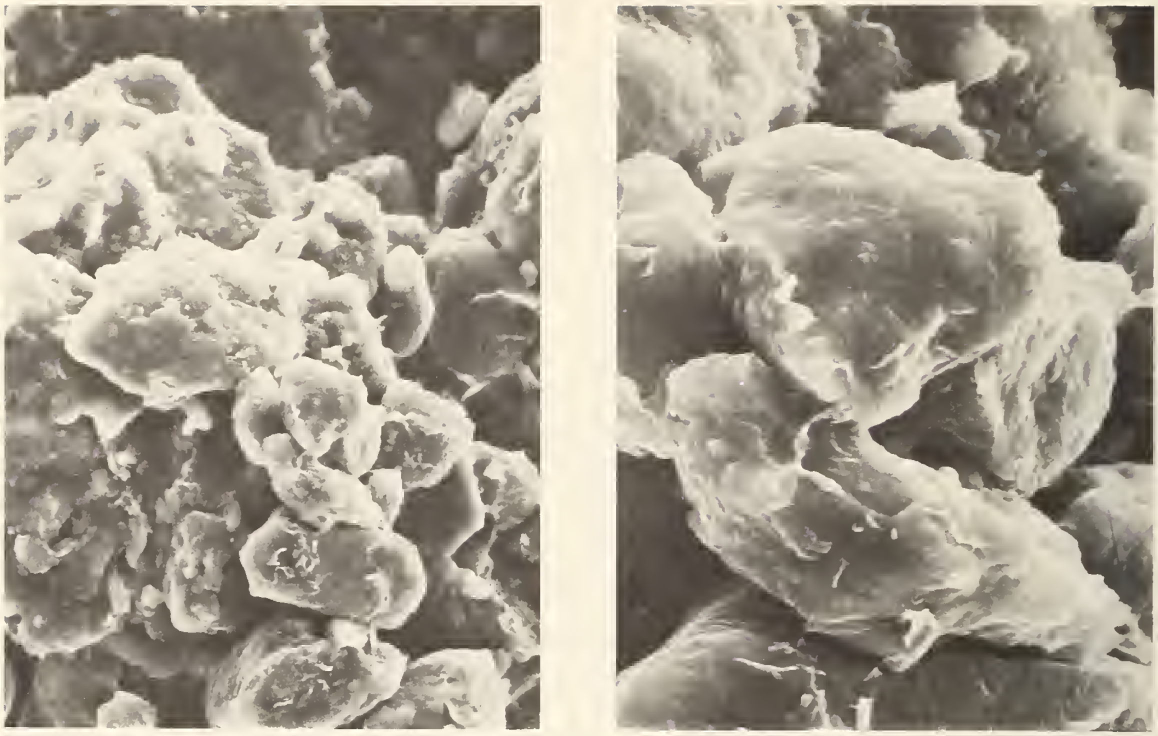
SITE <u>Holbrook, Ariz. (NO. 2, SH 180)</u> BORING <u>U-2</u> SAMPLE <u>No. 1</u> DEPTH <u>2.0-4.3 ft</u>



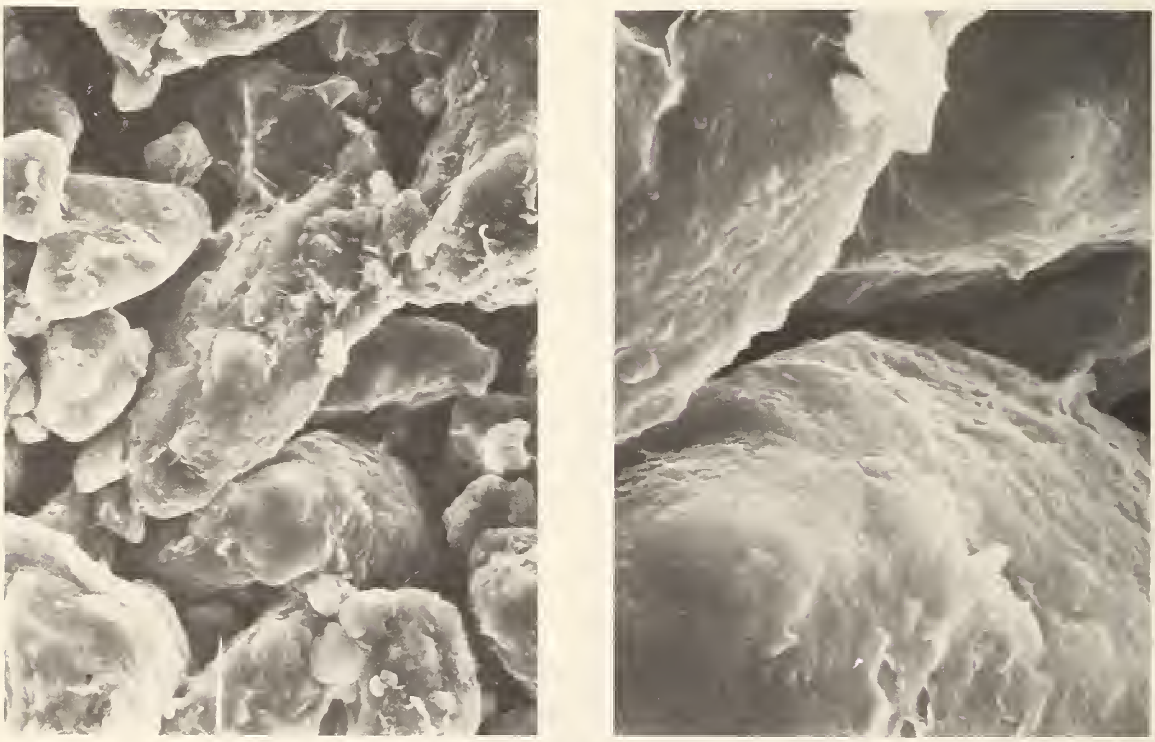
SOIL SUCTION VERSUS WATER CONTENT

SITE Holbrook, Ariz. (No. 2, SH 180) BORING U-2

SAMPLE No. 1 DEPTH 2.0-4.3 ft



a. Normal to Y, ×650 and ×2300

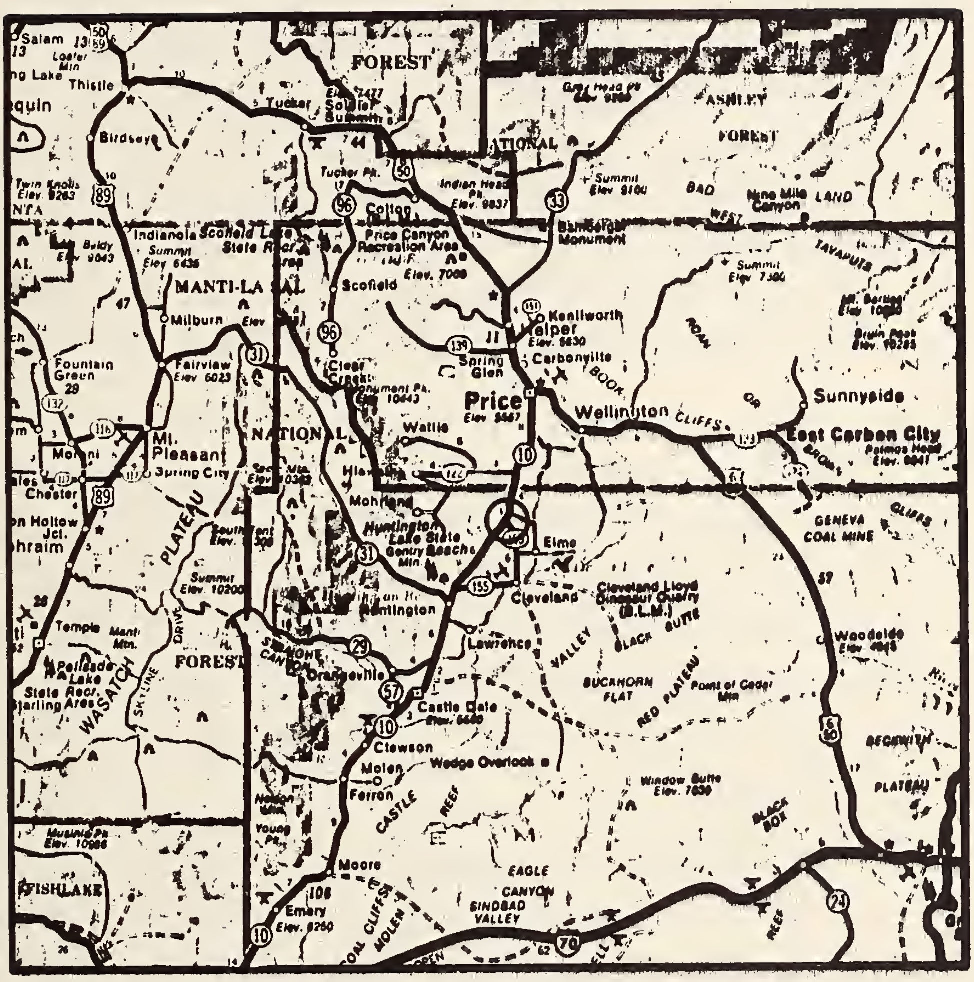


b. Normal to X, ×650 and ×2300

SITE Holbrook, Ariz. (No. 2, SH 180) BORING U-2

SAMPLE No. 1 DEPTH 2.0-4.3 ft

SAMPLING SITE NO. 11, PRICE, UTAH



Site Location Information

119. Sampling site No. 11 is located in east-central Utah, approximately 12 miles south of Price, Utah. The site is located approximately 2 miles south of Carbon-Emory County line on SH 10 and approximately 1/2 mile south of north junction of SH 10 and SH 155. Samples were taken in west verge slope adjacent to improved shoulder (≈ 25 ft from centerline).

Site Description

120. Sampling site is located in a cut section (depth ≈ 5 to 7 ft) in open, hilly terrain. Drainage is in a westerly direction on a gentle

to moderate slope. Surrounding area has a sparse grass cover and no trees.

Site Geology

121. Sampling site is located in the Canyon Lands Section of the Colorado Plateau Physiographic Province. Topography consists of canyoned plateaus with high relief. Samples were taken from the Mancos shale of the Upper Series of the Cretaceous System. The Mancos shale contains several significant sandstone layers and sandy facies and varies in thickness from a few hundred feet to as much as 6000 ft. The outcrop area is primarily concentrated in eastern Utah and western Colorado.

Sample Description

122. The Mancos shale as sampled is a hard, indurated, unweathered, gray (N5) clay shale exhibiting some bedding characteristics. Fractures and void spaces are not apparent in disturbed samples. Fresh and slightly weathered surfaces are calcareous. Small, shiney black spots and streaks, probably organic material, are common on many fragments. The SEM photographs indicate moderate particle orientation with wavey stratification.

Description of Climate

123. Utah's climate is determined by its distance from the equator; its elevation above sea level; the location of the State with respect to the average storm paths over the Intermountain Region; and its distance from the principal moisture sources of the area, namely, the Pacific Ocean and the Gulf of Mexico. Also, the mountain ranges over the western United States, particularly the Sierra Nevada and Cascade Ranges and the Rocky Mountains, have a marked influence on the climate of the State. Pacific storms, before reaching Utah, must first cross the Sierras or Cascades. As the moist air is forced to rise over these high mountains, a large portion of the original moisture falls as precipitation. Thus, the prevailing westerly air currents reaching Utah are comparatively dry, resulting in light precipitation over most of the State.

124. Precipitation varies greatly, from an average of less than

5 in. annually over the Great Salt Lake Desert (west of Great Salt Lake), to more than 40 in. in some parts of the Wasatch Mountains. The average annual precipitation in the leading agricultural areas is between 10 and 15 in., necessitating the practice of irrigation for the economic production of most crops. However, the mountains, where winter snows form the chief reservoirs of moisture, are conveniently adjacent to practically all farming areas, and there is usually sufficient water for most lands under irrigation. The areas of the State below an elevation of 4000 ft, all in the southern part, receive generally less than 10 in. of moisture annually.

125. Northwestern Utah, over and along the mountains, receives appreciably more precipitation in a year than is received at similar elevations over the rest of the State, primarily due to terrain and the direction of normal storm tracks. The bulk of the moisture occurring over that area can be attributed to the movement of Pacific storms through the region during the winter and spring months. In summer, north-western Utah is comparatively dry. The eastern portion receives appreciable rain from summer thunderstorms, which are usually associated with moisture-laden air masses moving in from the Gulf of Mexico.

126. There are definite variations in temperature with altitude and with latitude. Naturally, the mountains and the elevated valleys have the cooler climates, with the lower areas of the State having the higher temperatures. There is about a 3°F decrease in mean annual temperature for each 1000 ft increase in altitude, and approximately 1.5 to 2.0°F decrease in average yearly temperature for each 1° increase in latitude. Thus, weather stations in the southern tier of counties generally have average annual temperatures 6 to 8°F higher than those at similar altitudes over the extreme northern counties.

127. Utah experiences relatively strong insolation during the day and rapid nocturnal cooling, resulting in wide daily ranges in temperature. At Richfield, for example, the average annual daily variation from high to low is 35°F; and on individual days a range of 50 to 60°F is not uncommon. Even after the hottest days, nights are usually cool over the State.

128. Sunny skies prevail most of the year in Utah. For example, there is an average of about 65 to 75 percent of the possible amount of sunshine at Salt Lake City during spring, summer, and fall. In winter, Salt Lake City has about 50 percent of the possible sunshine.

Climatic Data Summary

Reporting Station: Hiawatha (42-3896-05) for 1941-70
Castle Dale (42-1214-07) for 1971-75

Mean Monthly Temperature and Normal
Monthly Precipitation for Period 1941-70:

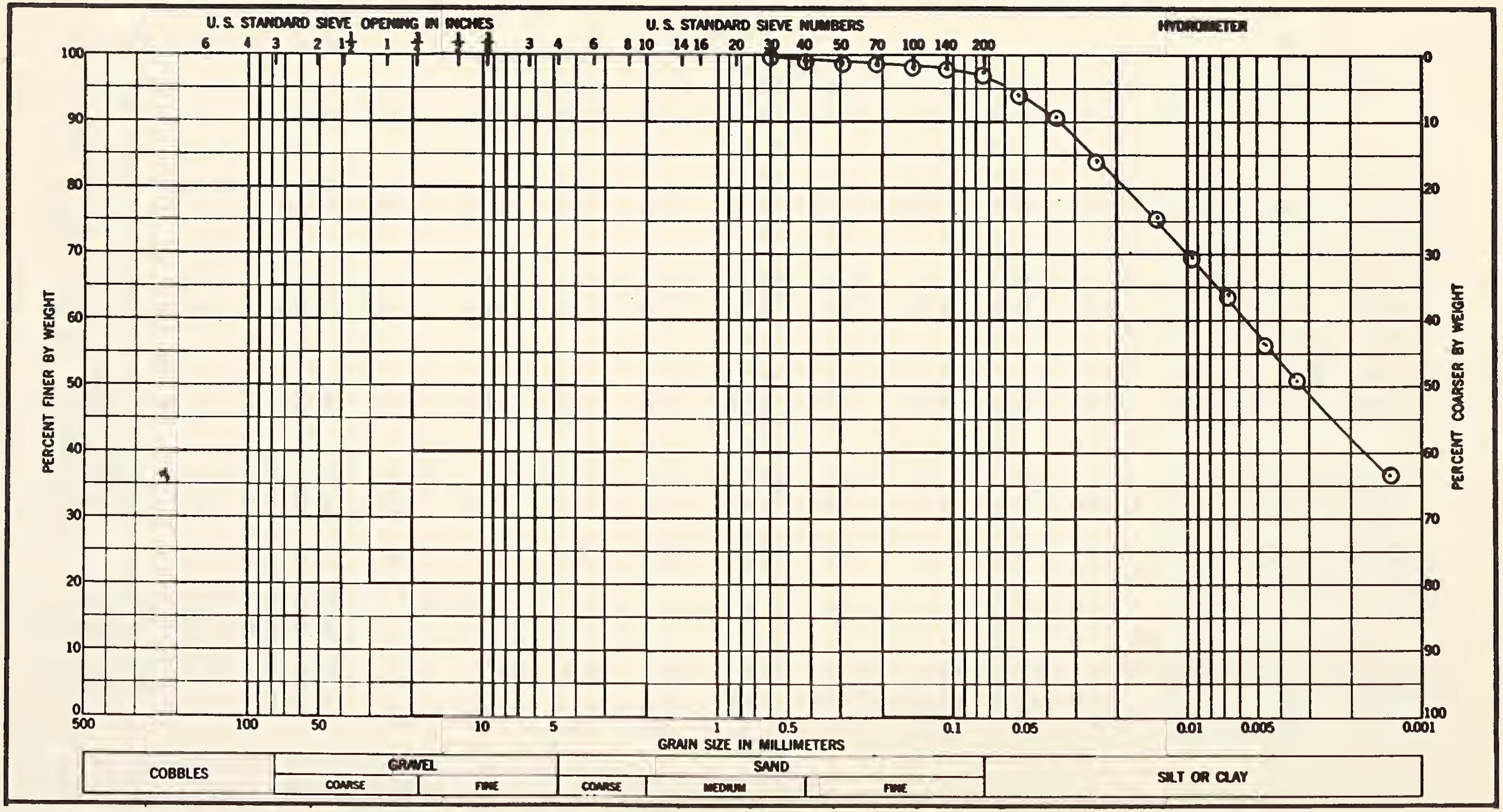
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature, °F	23.7	27.5	32.9	43.2	52.6	61.2	69.2	66.9	59.6	48.5	34.1	26.1	45.5
Precipitation, in.	1.06	0.87	1.03	1.06	1.10	1.25	1.13	1.99	1.19	1.35	0.85	1.27	14.15

Average Monthly Temperature and
Total Monthly Precipitation for 1971-75:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1971													
Temperature, °F	24.7	30.2	36.3	46.7	54.1	66.3	73.7	72.8	57.1	46.2	32.6	21.1	46.8
Precipitation, in.	0.31	0.62	0.00	0.21	0.76	0.16	0.19	0.54	0.05	1.63	0.21	0.94	5.62
1972													
Temperature, °F	27.3	33.6	44.8	48.0	57.4	66.8	72.7	69.0	59.8	49.8	32.5	20.3	48.5
Precipitation, in.	0.00	0.00	0.00	0.47	0.00	0.92	0.17	0.67	0.85	2.65	1.17	0.27	7.17
1973													
Temperature, °F	15.1	24.6	36.4	44.2	56.9	65.2	70.9	69.9	60.3	50.0	35.0	26.7	46.3
Precipitation, in.	0.42	0.71	0.97	1.18	0.23	0.54	0.91	0.42	0.07	0.17	0.19	0.14	5.95
1974													
Temperature, °F	15.8	20.4	42.7	44.2	59.1	68.7	71.7	68.4	60.6	50.6	35.7	24.6	46.9
Precipitation, in.	0.94	0.08	0.09	0.00	0.00	0.05	1.41	0.11	0.25	1.89	0.63	0.18	5.63
1975													
Temperature, °F	20.8	28.9	36.8	39.7	52.1	60.8	71.4	67.4	60.3	47.5	33.5	27.1	45.5
Precipitation, in.	0.29	0.23	0.85	0.06	0.21	1.01	1.34	0.11	0.31	0.13	0.36	0.02	4.92

Thornthwaite Moisture Index:

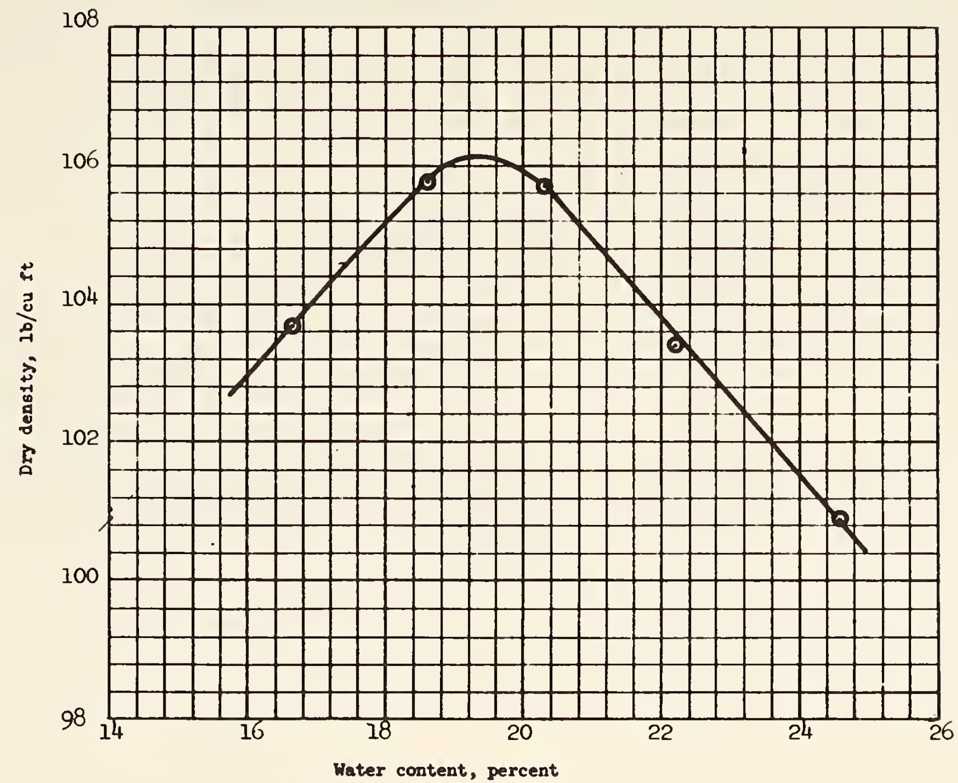
1970	1971	1972	1973	1974	1975	
-39.12	-44.13	-40.33	-20.30	-41.99	-32.75	Avg = -36.44



GRADATION CURVE

SITE Price, Utah BORING U-1

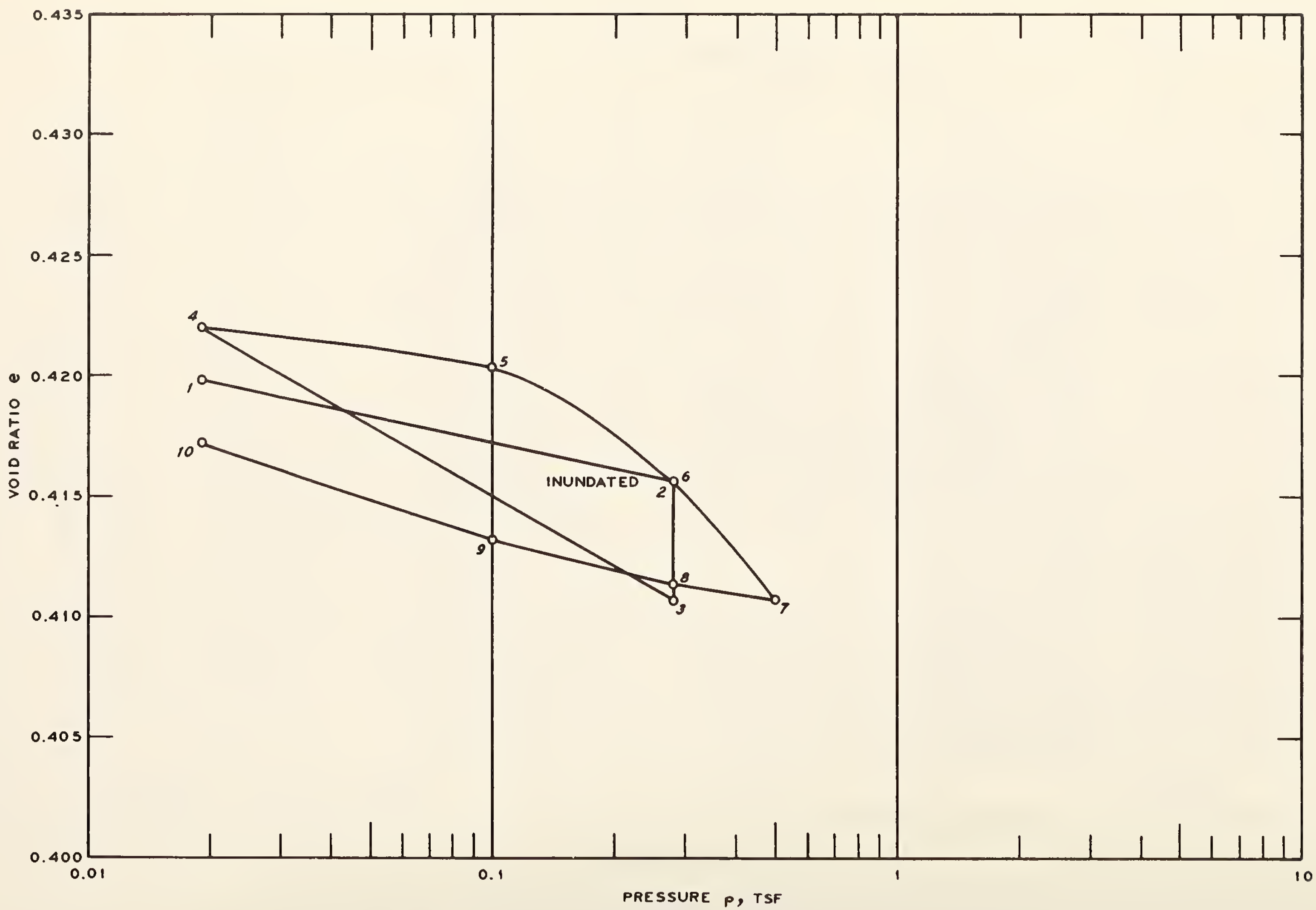
SAMPLE No. 1 DEPTH 1.2-3.2 ft



COMPACTION CURVE

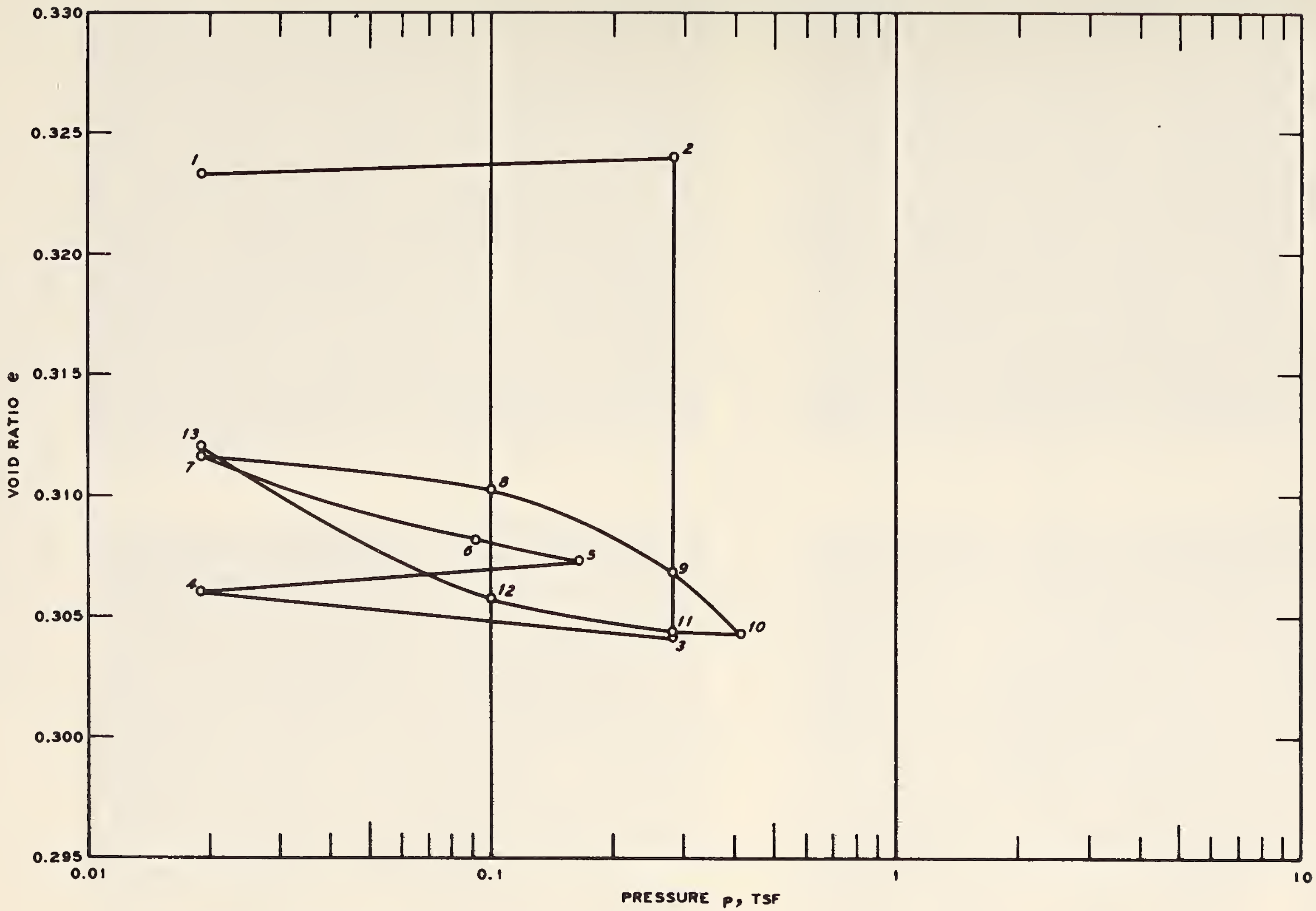
SITE Price, Utah

SAMPLE Disturbed



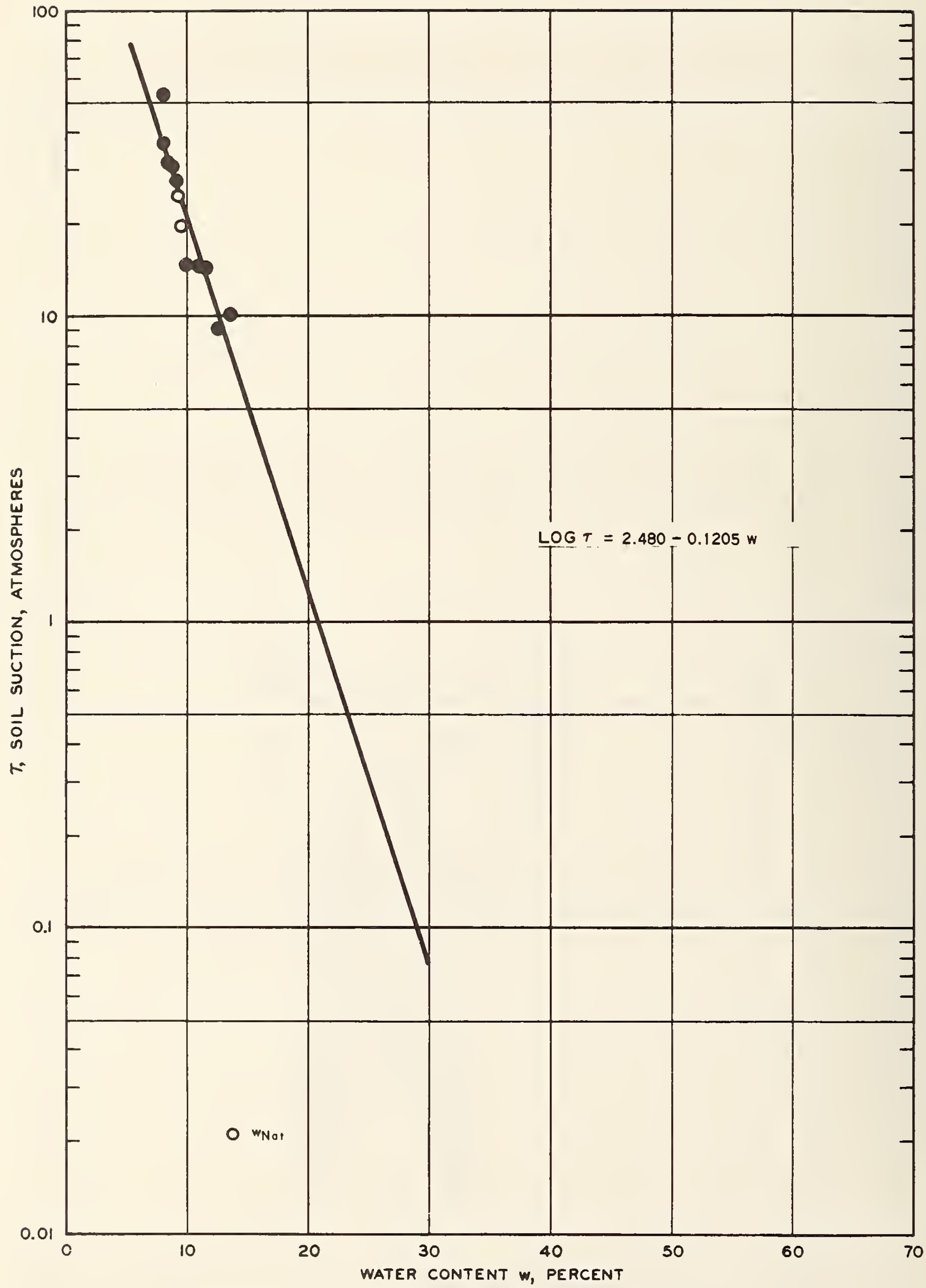
OVERBURDEN SWELL TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

SITE <u>Price, Utah</u> BORING <u>U-1</u> SAMPLE <u>No. 1</u> DEPTH <u>1.2-3.2 ft</u>



CONSTANT VOLUME SWELL PRESSURE TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

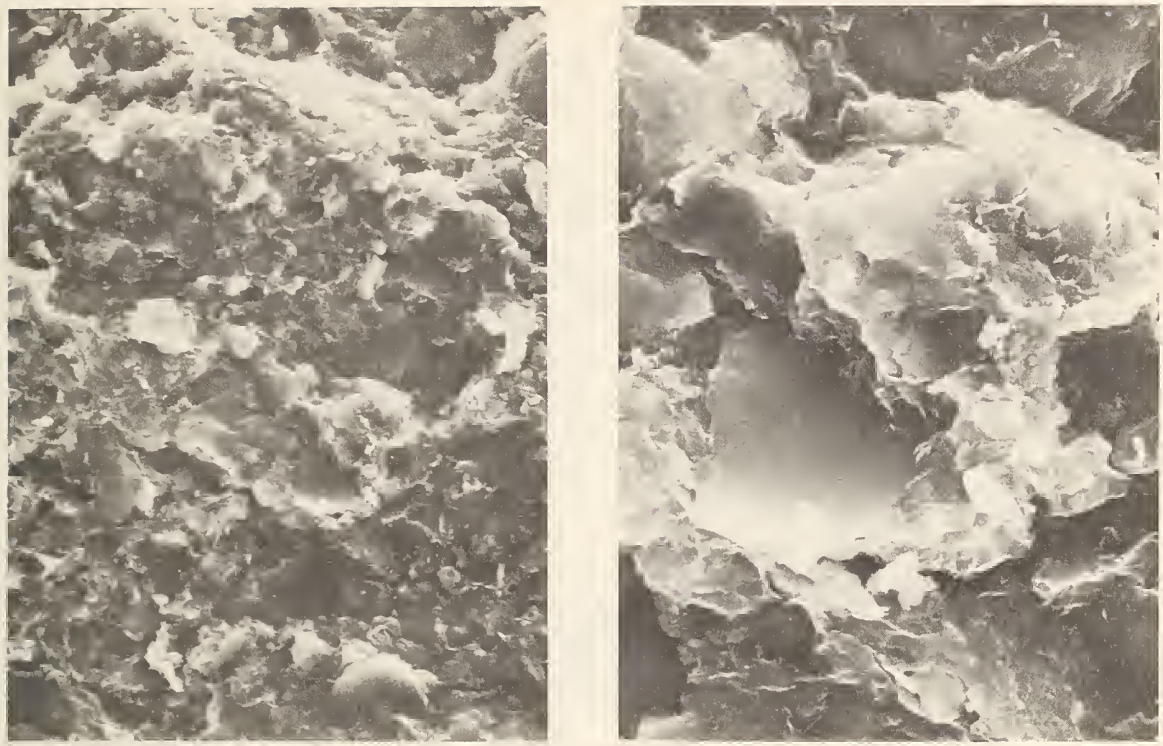
SITE <u>Price, Utah</u> BORING <u>U-1</u> SAMPLE <u>No. 1</u> DEPTH <u>1.2-3.2 ft</u>



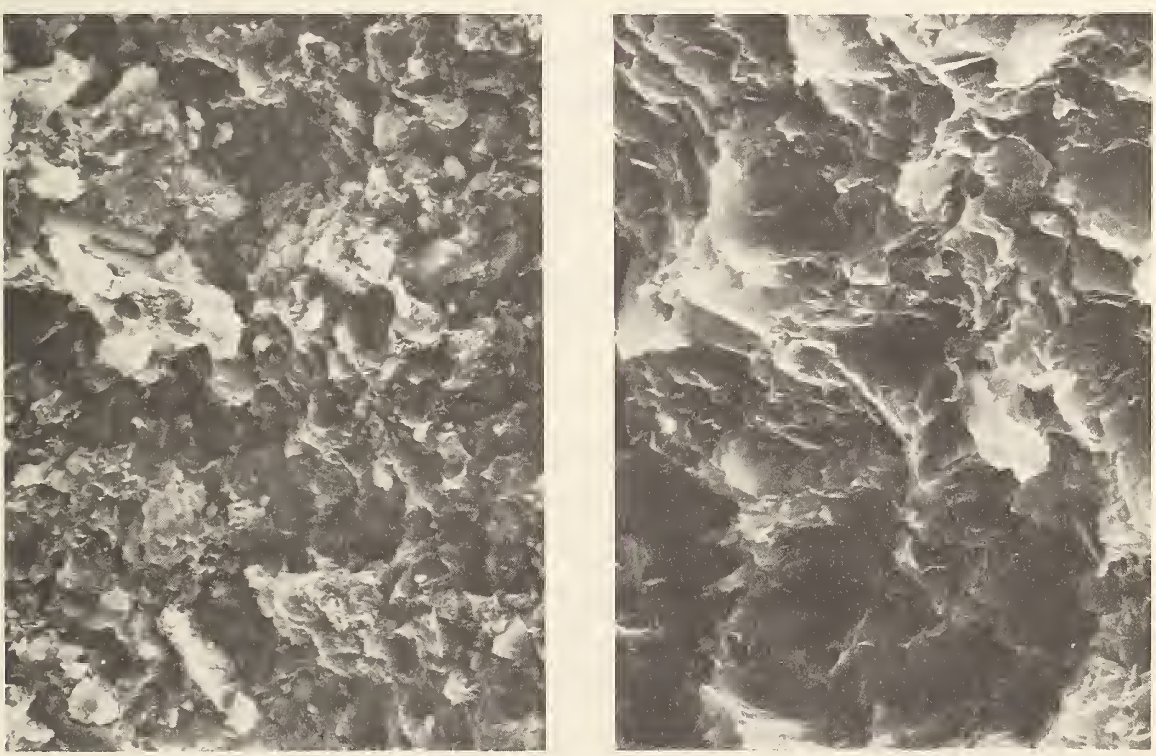
SOIL SUCTION VERSUS WATER CONTENT

SITE Price, Utah BORING U-1

SAMPLE No. 1 DEPTH 1.2-3.2 ft



a. Normal to Y, ×650 and ×2300



10 μm

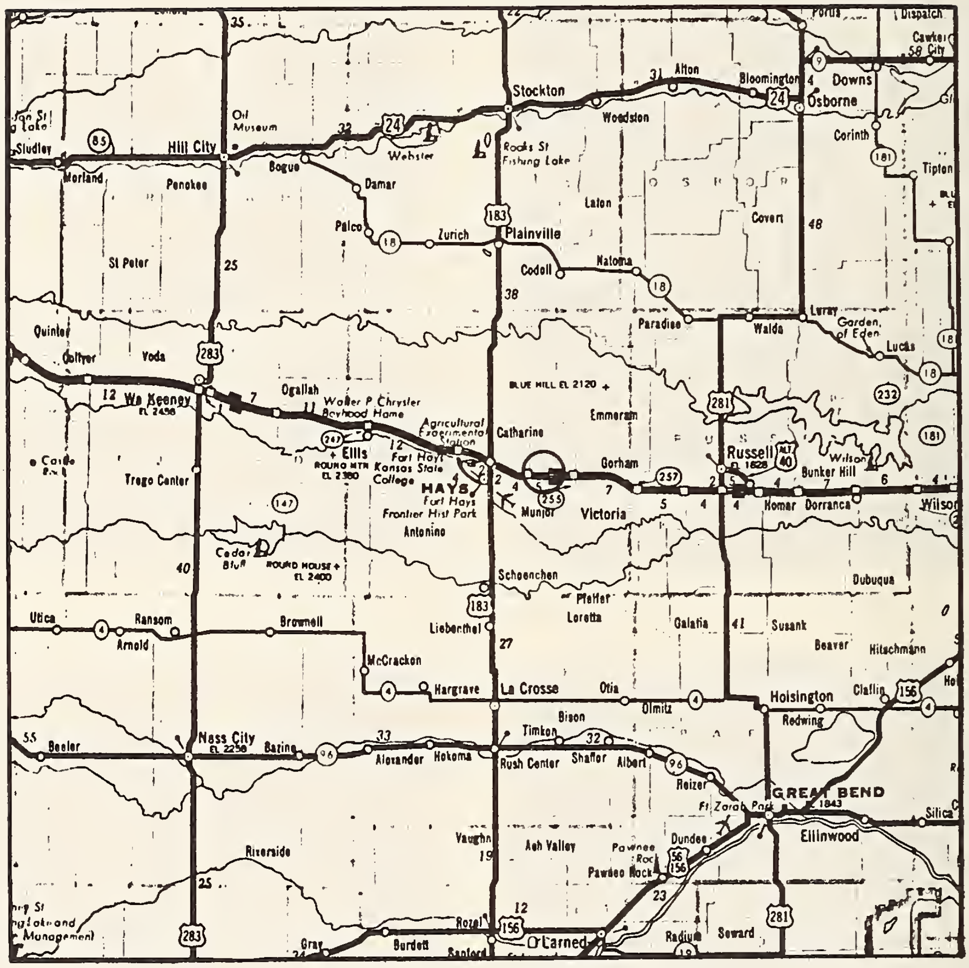
b. Normal to X, ×650 and ×2300

10 μm

SITE Price, Utah BORING U-1

SAMPLE No. 1 DEPTH 1.2-3.2 ft

SAMPLING SITE NO. 12, HAYS, KANS.



Site Location Information

129. Sampling site No. 12 is located in west-central Kansas approximately 5 miles east of Hays, Kans. Site is located approximately 1.5 miles east of Toulan Interchange on I-70. Samples were taken from south verge slope of eastbound lane ($\approx$ 40 ft south of centerline) 750 ft east of milepost 165. The area is in a cut section in the NW 1/4 of SE 1/4, section 33, T13S, R17W.

Site Description

130. Sampling site is located in a cut section (depth $\approx$ 15 to 18 ft) in open rolling terrain. Drainage is in a northerly direction on

a gentle to moderate slope. Surrounding area has a full grass cover and no trees.

Site Geology

131. Sampling site is located in the Plains Border Section of the Great Plains Physiographic Province. Topography is one of maturely dissected plateaus and rolling hills. Samples were taken from the Blue Hill member, Carlile Formation, Colorado Group, Gulfian Series. The Blue Hill member consists primarily of dark gray, noncalcareous shale with septarian concretions and selenite crystals and contains some sandstones in its upper portions. The Blue Hill overlies the Fairport chalky shale member of the Carlile Formation and underlies the Ft. Hays limestone member of the Niobrara Formation. The thickness of the Blue Hill varies from approximately 75 to 200 ft and is exposed in a band extending from central Kansas northeast to Nebraska.

Sample Description

132. The Blue Hill shale as sampled is a hard indurated, noncalcareous, partly weathered, mottled light gray (N6) which predominates to pale yellowish orange (10 YR 8/6) clay shale. Distinct stratification and bedding plane fractures are visible, but no other voids are apparent. Some accessory mica are present. The SEM photographs indicate a well-developed, face-to-face particle orientation.

Description of Climate

133. Located at the geographical center of the contiguous 48 States, Kansas has a distinctly continental climate with characteristically changeable temperature and precipitation.

134. Kansas weather is affected largely by two physical features, both some distance from the State, the Rocky Mountains to the west and the Gulf of Mexico to the south. The mountains on the west prevent the importation of moisture from the Pacific Ocean, while the Gulf is the feeding source for much of the State's precipitation.

135. A third factor, differences in elevation, also influences the climate. Elevation changes are quite gradual, rising from 800 or 1000 ft above sea level in a number of extreme eastern and southeastern counties to approximately 1500 ft about the centerline of the State,

north to south, and to 3500 ft at the Colorado line. Quite coincident with these gradations is a change in climate as described by Thronthwaite:

> Humid in the extreme east, moist subhumid from there to just west of the midpoint, to dry subhumid in the west with the extreme southwest designated semiarid. A corresponding change in crop growth is noted from corn, tall grasses, and other moisture demanding crops in the east to the drought resistant sorghums, short grasses, and small grains in the west.

136. Average annual precipitation totals range from slightly more than 40 in. in the southeastern counties to 30 to 35 in. in the northeast, decreasing gradually westward to the Colorado line where the average is from 16 to 18 in. Distribution of rainfall through the year favors crop production, with an average of about 75 percent of the year's total falling in the crop growing season, April to September. January, the month of least precipitation, has an average of 1 to 2 in. at the more eastern stations, decreasing to less than an inch over the western three fourths of the State and to near a quarter inch in the extreme west. May and June, in contrast, are the months of greatest rain with between 4 and 5 in. on the average in the eastern three fifths of the State to between 2 and 3 in. in the western counties. In addition to the seasonal changes of precipitation amounts over the State, there is a secondary fluctuation in the average rainfall which is quite pronounced in the east. In this area a noticeable decrease in the average rainfall occurs during the latter part of July and the forepart of August, with an increase again in September. This decrease in rainfall occurs at the critical period for corn.

137. Precipitation is most frequent in the extreme east where on the average measurable amounts are recorded on 90 to 100 days of the year. The average annual number of days with an inch or more of precipitation is 60 to 80 over two thirds of the central portion and about 70 in the northwestern portion, but decreases to near 50 in the southwestern section.

138. Snowfall averages near 10 in. a year in the south-central counties and increases gradually in other parts of the State to the

largest average of 24 in. in the northwest. Snow has been recorded in all months except July and August, the greatest average fall is in February with March snows only slightly less. Falls of 12 to 24 in. in 24 hr have been recorded in most sections. Ordinarily snow remains on the ground only a short time, but during the winter the ground may be snow-covered from 10 to 15 days in the south and from 30 to 35 days in the north. In rare instances snow has covered the ground continuously in western and northern sections from 40 to 60 days.

139. Wet and dry trends or periods are noted in the longer records. Dry periods may presist for several years with an occasional interim of a month or two of above average rainfall. There appears to be some indication of recurring patterns of years with similar trends but records are too short to establish this with certainty.

140. The annual mean temperature ranges from about 58°F along the south-central and southeastern border to 52°F in the extreme northwest. Monthly mean temperatures in the northwest range from about 28°F in January to near 78°F in July, and in the southeast and south-central from 34°F in January to 80 or 81°F in July. Daily temperature ranges, on the average, increase from 20°F in the east to 30°F in the higher and drier elevations of the northwest.

141. During much of the year there is a progressive increase in mean temperature from the higher northwestern counties to the southeastern area. The exception is during the warm summer months when the higher mean temperatures are found in the central and south-central counties.

142. The prevailing winds are from a southerly direction with the exception of the cold months of December through March which have considerable wind from the north or northwest. Generally the extreme winds are from a northerly direction. In the western part of the State wind speeds are higher and average about 15 mph, approximately 5 mph faster than in the eastern sections.

Climatic Data Summary

Reporting Station: Hays 1S (14-3527-05)

Mean Monthly Temperature and Normal
Monthly Precipitation for Period 1941-70:

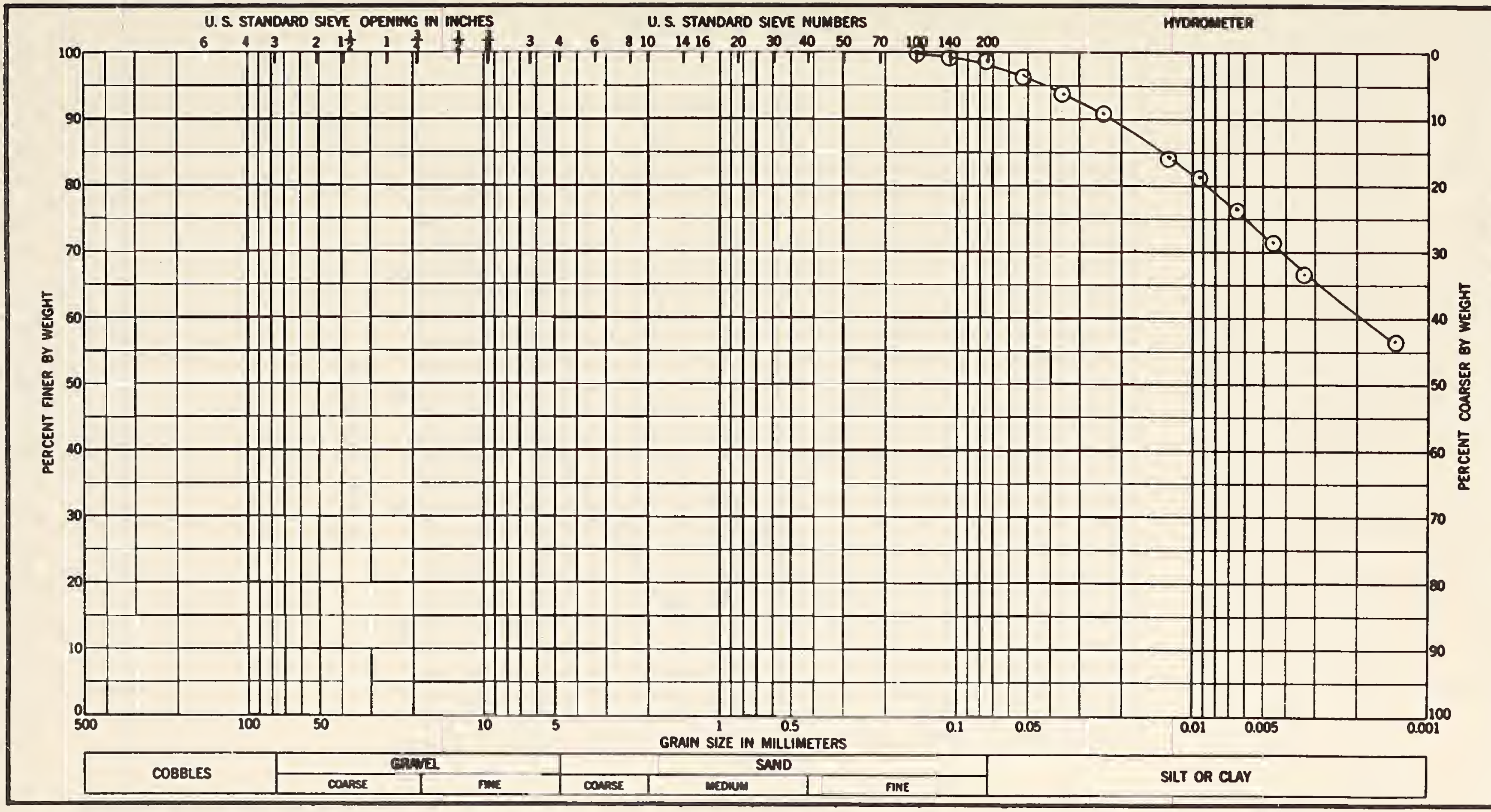
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature, °F	27.8	32.5	39.2	52.9	62.9	73.0	78.6	7.77	68.0	56.5	41.1	30.7	53.4
Precipitation, in.	0.36	0.66	1.18	1.91	3.51	4.46	3.43	2.78	2.52	1.39	0.66	0.48	23.34

Average Monthly Temperature and
Total Monthly Precipitation for 1971-75:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1971													
Temperature, °F	25.3	28.1	38.7	53.2	59.1	76.7	75.7	75.6	66.9	57.3	42.1	29.3	52.3
Precipitation, in.	0.45	1.99	0.28	3.14	4.56	1.86	4.18	0.79	0.47	2.53	2.67	0.83	23.75
1972													
Temperature, °F	25.5	32.2	46.6	52.4	61.8	72.8	75.4	74.4	66.6	52.2	36.3	23.9	51.7
Precipitation, in.	0.07	0.00	0.35	1.52	3.77	3.26	2.57	5.70	1.48	0.57	2.54	0.56	22.39
1973													
Temperature, °F	27.0	33.4	44.1	49.4	59.1	73.9	78.3	78.1	63.2	56.5	40.9	28.7	52.7
Precipitation, in.	0.61	0.20	7.92	1.90	2.49	0.73	6.34	3.45	5.02	3.03	1.23	2.08	35.00
1974													
Temperature, °F	22.1	36.6	44.7	54.0	64.7	71.5	81.7	72.5	61.5	57.7	41.8	30.3	53.3
Precipitation, in.	0.18	0.06	1.10	1.45	1.70	2.99	1.54	2.56	0.22	2.43	0.76	0.24	15.23
1975													
Temperature, °F	31.9	27.0	34.5	50.6	62.7	70.4	78.2	79.1	64.9	56.3	40.2	34.4	52.5
Precipitation, in.	0.27	0.87	0.92	3.29	3.86	6.61	0.09	2.09	1.28	0.00	3.29	0.03	22.60

Thornthwaite Moisture Index:

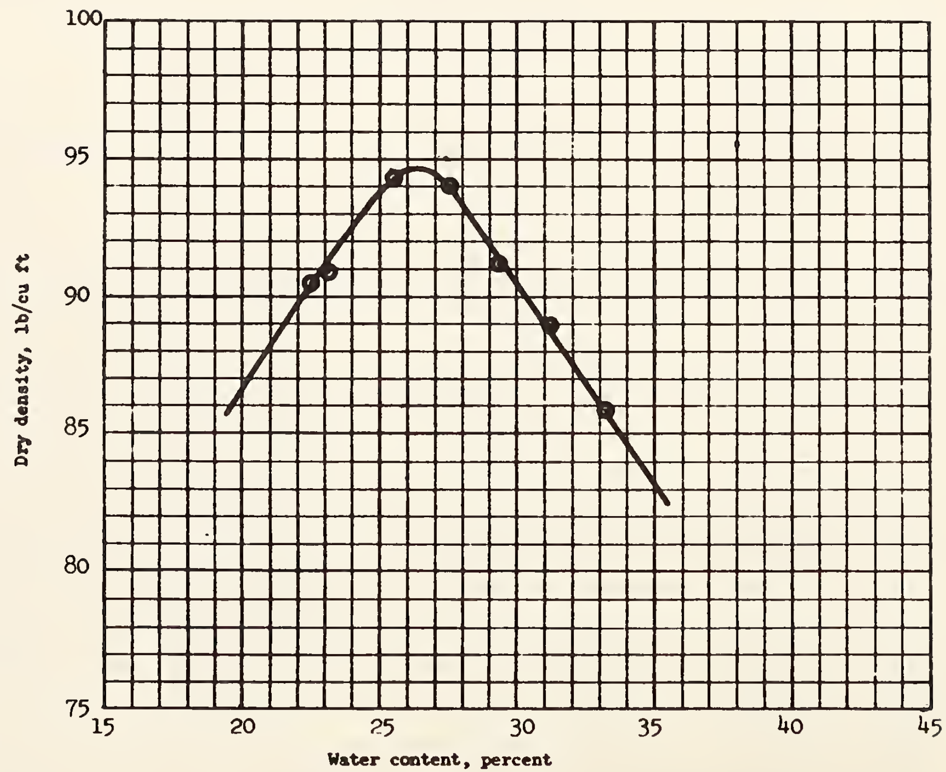
1970	1971	1972	1973	1974	1975	
-6.77	2.93	2.12	50.21	2.19	3.91	Avg = 9.1



GRADATION CURVE

SITE Hays, Kans. BORING U-2

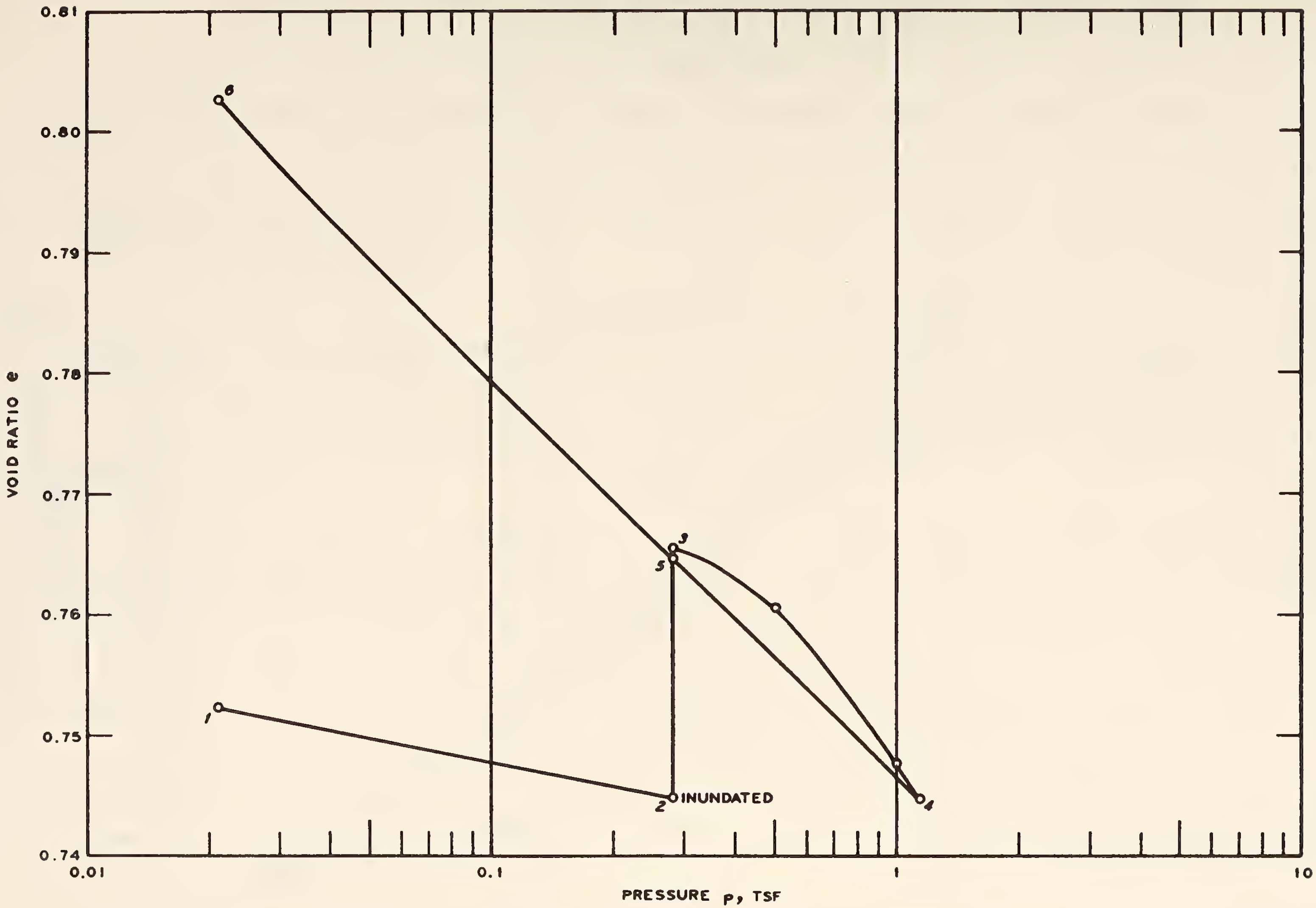
SAMPLE No. 1 DEPTH 1.4-3.4 ft



COMPACTION CURVE

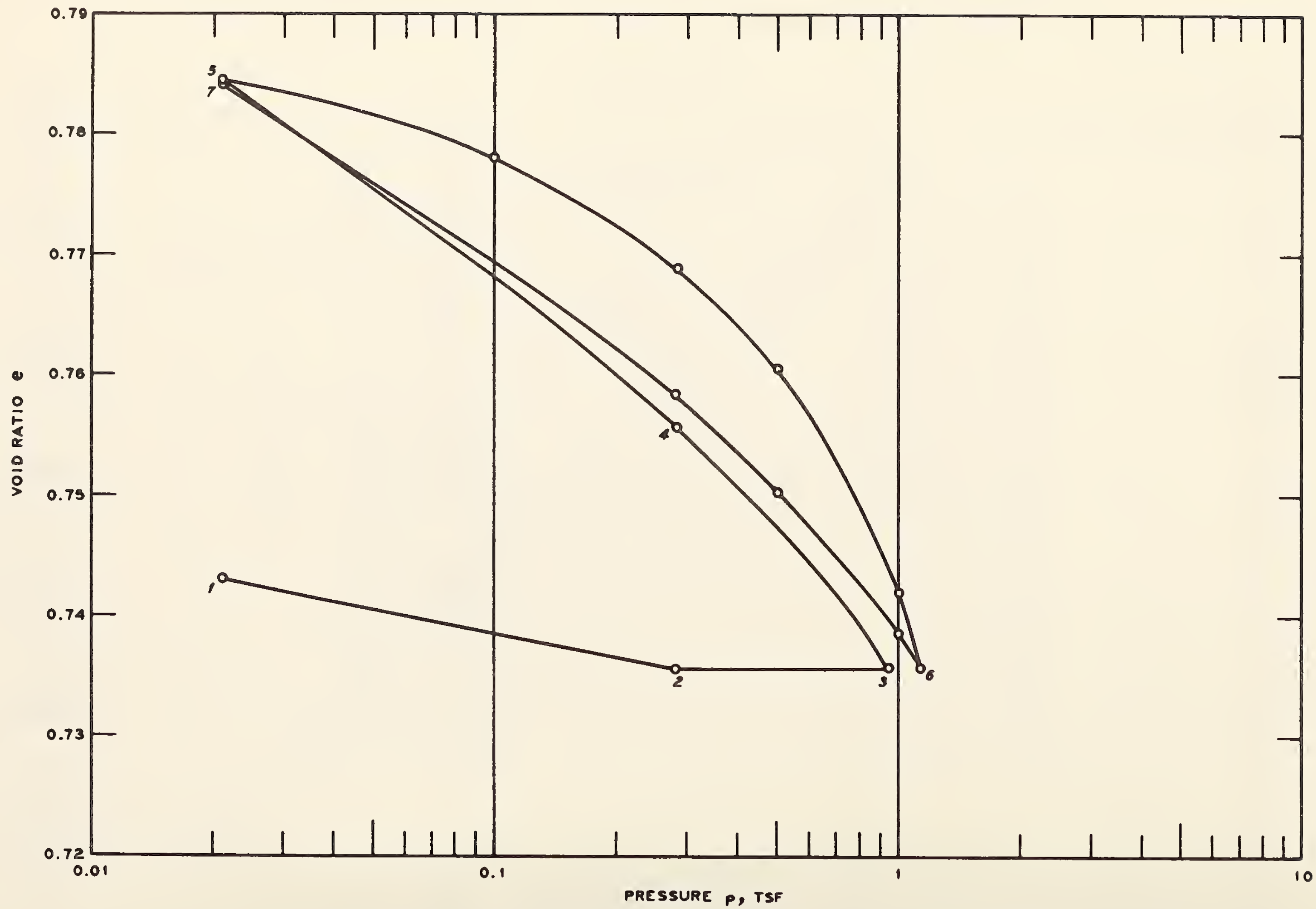
SITE Hays, Kans.

SAMPLE Disturbed



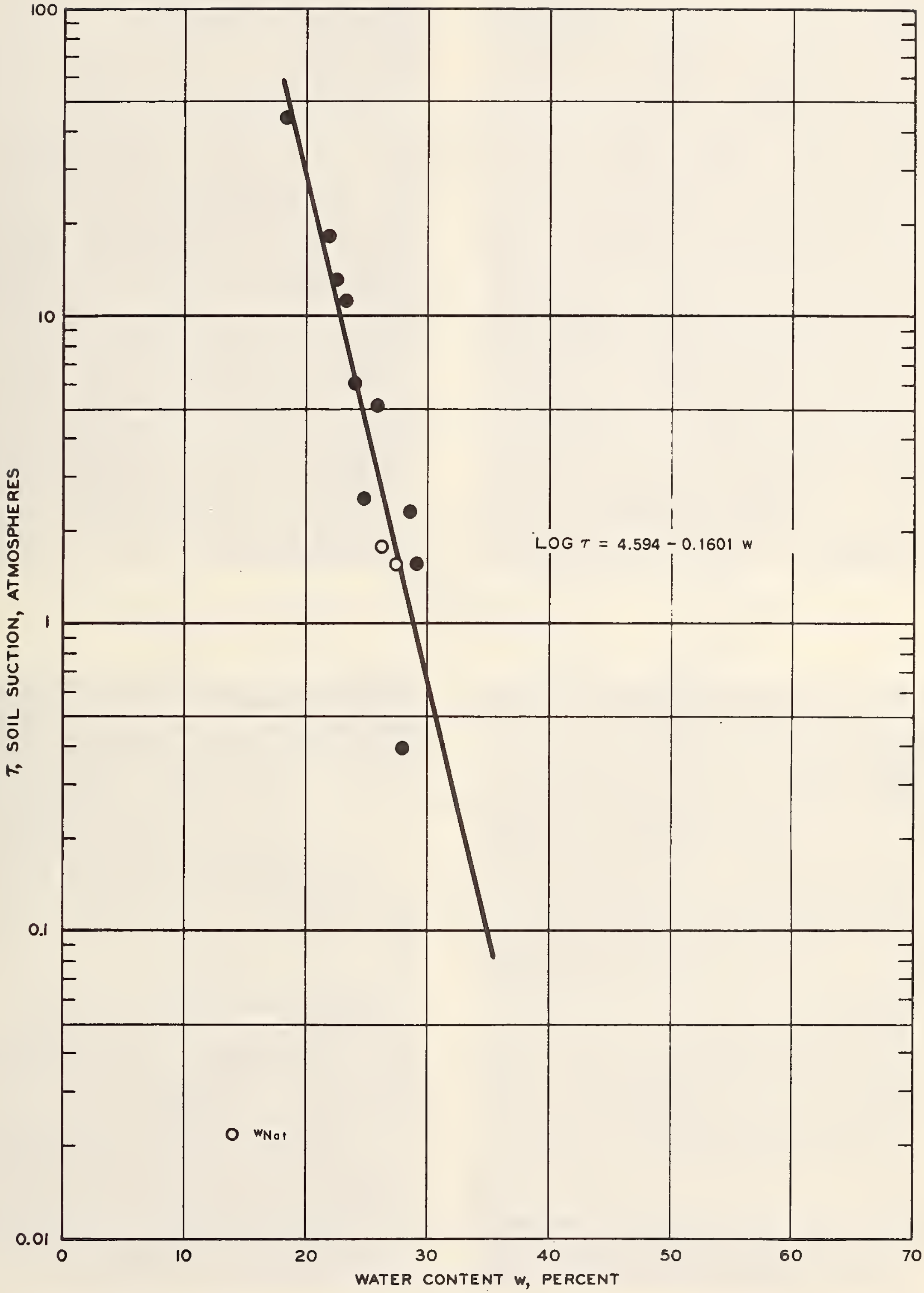
OVERBURDEN SWELL TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

SITE Hays, Kans. BORING U-2 SAMPLE No. 1 DEPTH 1.4-3.4 ft



CONSTANT VOLUME SWELL PRESSURE TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

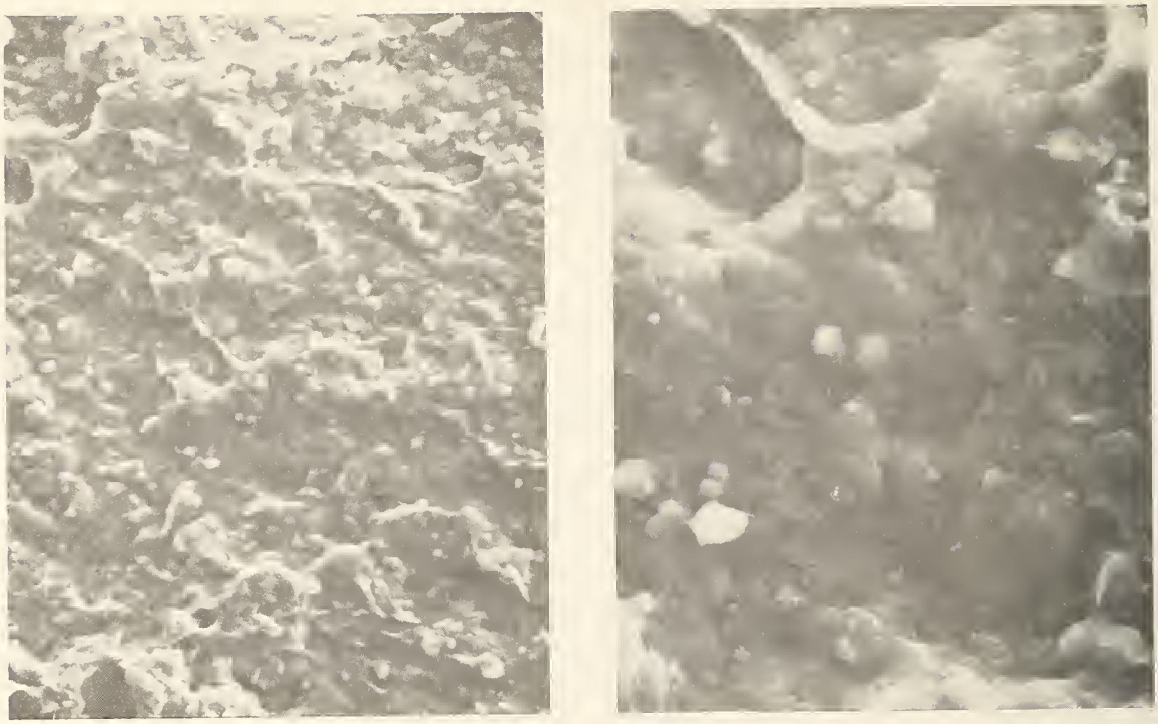
SITE Hays, Kans. BORING U-2 SAMPLE No. 1 DEPTH 1.4-3.4 ft



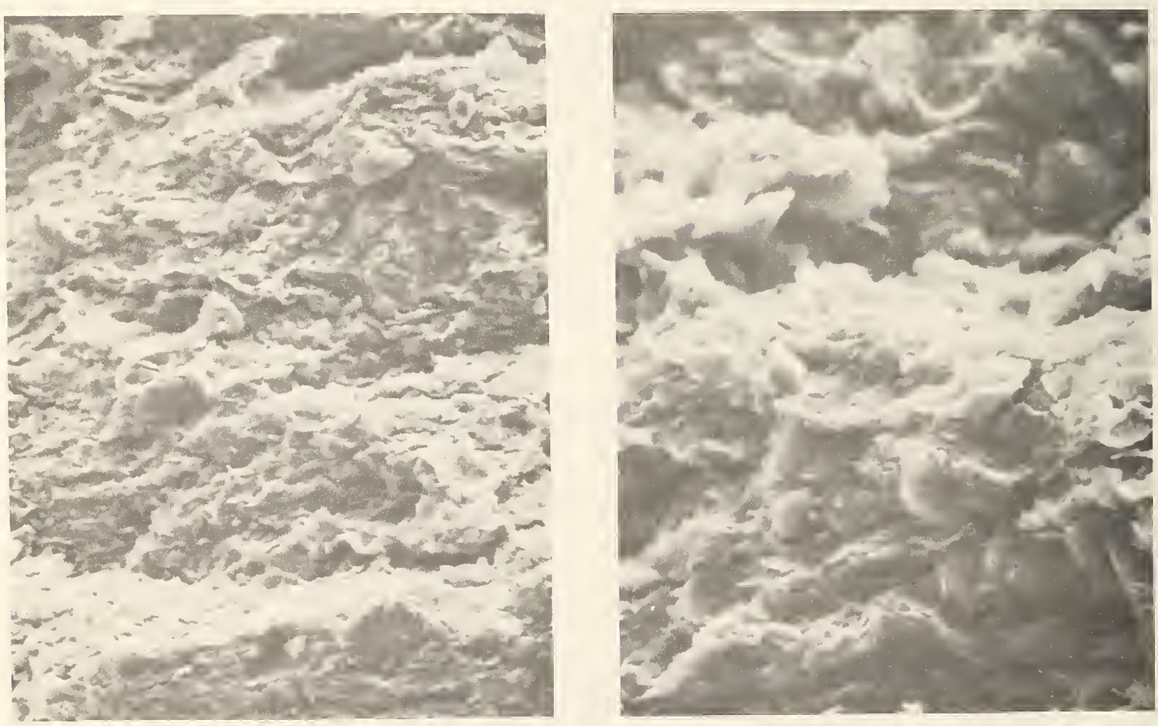
SOIL SUCTION VERSUS WATER CONTENT

SITE Hays, Kans. BORING U-2

SAMPLE No. 1 DEPTH 1.4-3.4 ft



a. Normal to Y, ×650 and ×2300



10 μm

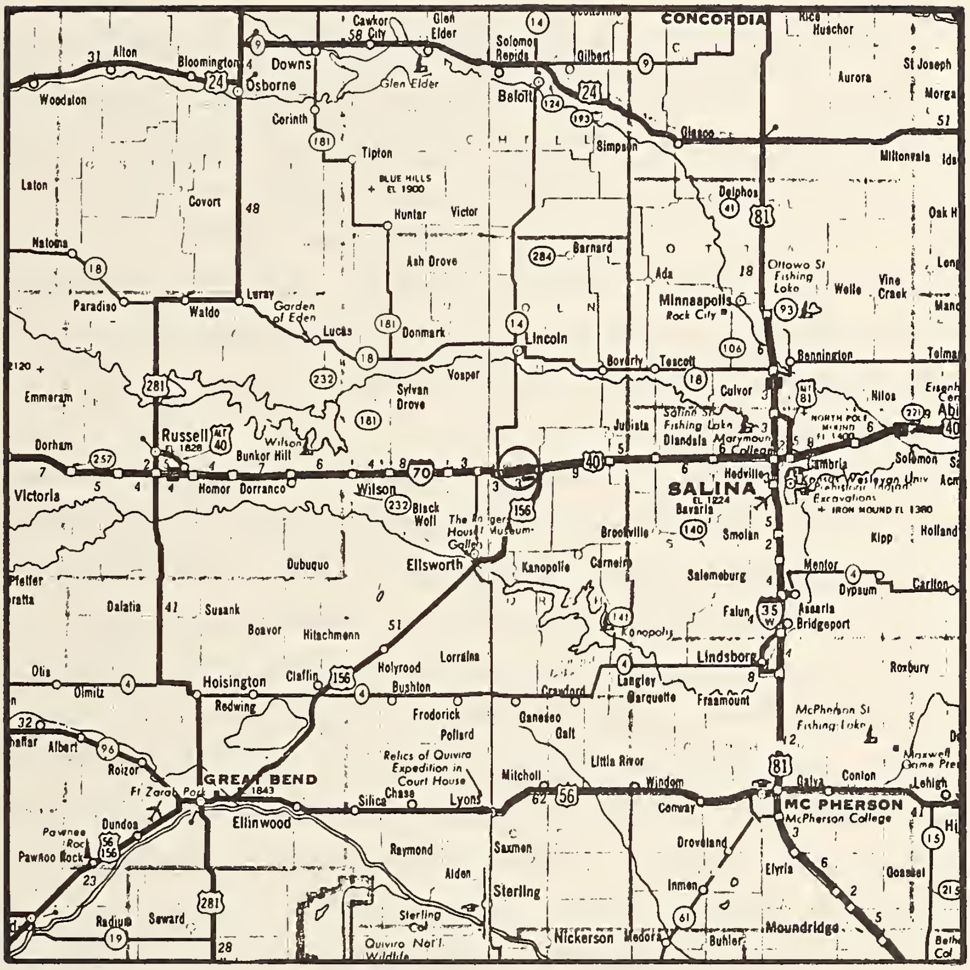
b. Normal to X, ×650 and ×2300

10 μm

SITE Hays, Kans. BORING U-2

SAMPLE No. 1 DEPTH 1.4-3.4 ft

SAMPLING SITE NO. 13, ELLSWORTH, KANS.



Site Location Information

143. Sampling site No. 13 is located in west-central Kansas approximately 10 miles northeast of Ellsworth, Kans. The site is located approximately 1.5 miles west of I-70 and U. S. 156 junction on I-70. Samples were taken from median ($\approx$ 40 ft south of centerline of westbound lane) at milepost 223.34. The area is in a cut section in the NW 1/4 of NW 1/4 of section 7, T14S, R7W.

Site Description

144. Sampling site is located in a cut section (depth $\approx$ 10 to 12 ft) in hilly terrain. Drainage is in an easterly direction on a

gentle to moderate slope. Surrounding area has a nearly full grass cover and no trees.

Site Geology

145. Sampling site is located in the Plains Border Section of the Great Plains Physiographic Province. The topography is one of maturely dissected plateaus and rolling hills. Samples were taken from the Graneros Formation of the Colorado Group, Gulfian Series, Cretaceous System. The Graneros Formation is predominantly dark clay shale varying in thickness from approximately 30 to 65 ft. The Graneros overlies the sands of the Dakota Group and overlain by the Greenhorn limestone. The Graneros outcrops primarily in north-central Kansas.

Sample Description

146. The Graneros Formation as sampled is a moderately hard, indurated, relatively unweathered, highly calcareous, medium dark gray (N4) to dark gray (N3) clay shale. It exhibits well-developed stratification and fissility with white microlaminations of calcite along bedding planes. The microlaminations appear as irregular ovals or patches when viewed normal to the bedding. Some mica occurs as an accessory mineral. Voids and bedding plane separations or cracks are not abundant in unweathered samples. The SEM photographs show a massive appearance lacking appreciable detectable platelets with considerable cement.

Description of Climate

147. Located at the geographical center of the contiguous 48 States, Kansas has a distinctly continental climate with characteristically changeable temperature and precipitation.

148. Kansas weather is affected largely by two physical features, both some distance from the State, the Rocky Mountains to the west and the Gulf of Mexico to the south. The mountains on the west prevent the importation of moisture from the Pacific Ocean, while the Gulf is the feeding source for much of the State's precipitation.

149. A third factor, differences in elevation, also influences the climate. Elevation changes are quite gradual, rising from 800 or 1000 ft above sea level in a number of extreme eastern and southeastern counties to approximately 1500 ft about the centerline of the State,

north to south, and to 3500 ft at the Colorado line. Quite coincident with these gradations is a change in climate as described by Thronthwaite:

> Humid in the extreme east, moist subhumid from there to just west of the midpoint, to dry subhumid in the west with the extreme southwest designated semiarid. A corresponding change in crop growth is noted from corn, tall grasses, and other moisture demanding crops in the east to the drought resistant sorghums, short grasses, and small grains in the west.

150. Average annual precipitation totals range from slightly more than 40 in. in the southeastern counties to 30 to 35 in. in the northeast, decreasing gradually westward to the Colorado line where the average is from 16 to 18 in. Distribution of rainfall through the year favors crop production, with an average of about 75 percent of the year's total falling in the crop growing season, April to September. January, the month of least precipitation, has an average of 1 to 2 in. at the more eastern stations, decreasing to less than an inch over the western three fourths of the State and to near a quarter inch in the extreme west. May and June, in contrast, are the months of greatest rain with between 4 and 5 in. on the average in the eastern three fifths of the State to between 2 and 3 in. in the western counties. In addition to the seasonal changes of precipitation amounts over the State, there is a secondary fluctuation in the average rainfall which is quite pronounced in the east. In this area a noticeable decrease in the average rainfall occurs during the latter part of July and the forepart of August, with an increase again in September. This decrease in rainfall occurs at the critical period for corn.

151. Precipitation is most frequent in the extreme east where on the average measurable amounts are recorded on 90 to 100 days of the year. The average annual number of days with an inch or more of precipitation is 60 to 80 over two thirds of the central portion and about 70 in the northwestern portion, but decreases to near 50 in the southwestern section.

152. Snowfall averages near 10 in. a year in the south-central counties and increases gradually in other parts of the State to the

largest average of 24 in. in the northwest. Snow has been recorded in all months except July and August, the greatest average fall is in February with March snows only slightly less. Falls of 12 to 24 in. in 24 hr have been recorded in most sections. Ordinarily snow remains on the ground only a short time, but during the winter the ground may be snow-covered from 10 to 15 days in the south and from 30 to 35 days in the north. In rare instances snow has covered the ground continuously in western and northern sections from 40 to 60 days.

153. Wet and dry trends or periods are noted in the longer records. Dry periods may presist for several years with an occasional interim of a month or two of above average rainfall. There appears to be some indication of recurring patterns of years with similar trends but records are too short to establish this with certainty.

154. The annual mean temperature ranges from about 58°F along the south-central and southeastern border to 52°F in the extreme northwest. Monthly mean temperatures in the northwest range from about 28°F in January to near 78°F in July, and in the southeast and south-central from 34°F in January to 80 or 81°F in July. Daily temperature ranges, on the average, increase from 20°F in the east to 30°F in the higher and drier elevations of the northwest.

155. During much of the year there is a progressive increase in mean temperature from the higher northwestern counties to the southeastern area. The exception is during the warm summer months when the higher mean temperatures are found in the central and south-central counties.

156. The prevailing winds are from a southerly direction with the exception of the cold months of December through March which have considerable wind from the north or northwest. Generally the extreme winds are from a northerly direction. In the western part of the State wind speeds are higher and average about 15 mph, approximately 5 mph faster than in the eastern sections.

Climatic Data Summary

Reporting Station: Ellsworth (14-2459-05)

Mean Monthly Temperature and Normal
Monthly Precipitation for Period 1941-70:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature, °F	29.7	34.6	41.9	55.5	65.2	75.3	80.5	79.5	69.5	58.6	43.2	32.8	55.5
Precipitation, in.	0.67	0.97	1.71	2.52	3.81	4.37	3.62	3.02	3.47	2.08	0.95	0.90	28.09

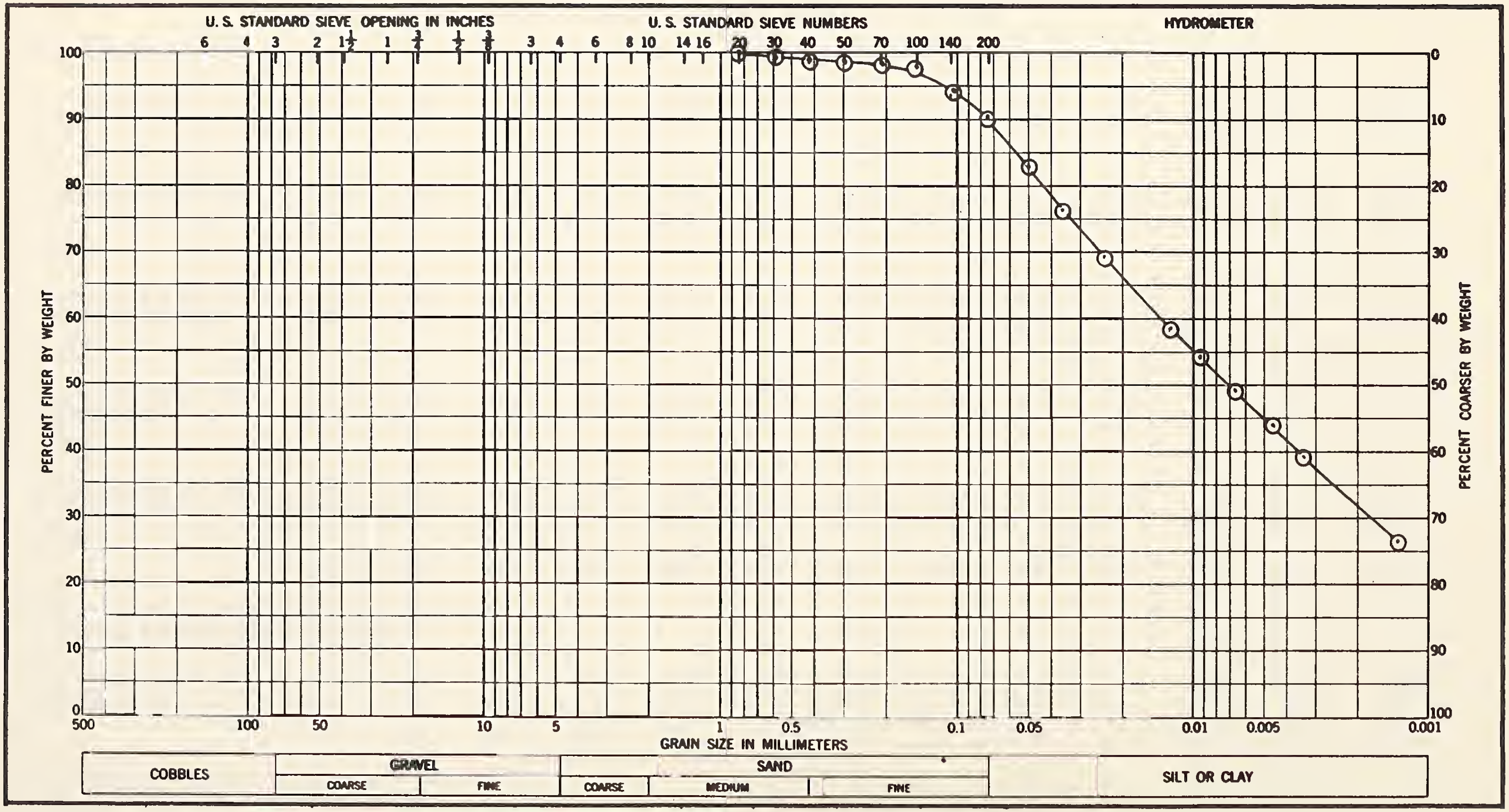
Average Monthly Temperature and
Total Monthly Precipitation for 1971-75:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1971													
Temperature, °F	26.3	28.2	41.5	55.8	62.7	77.5	77.5	77.5	70.5	60.3	44.1	35.9	54.8
Precipitation, in.	0.90	2.33	0.62	1.38	6.33	5.72	6.47	0.70	1.27	5.62	2.52	0.33	34.19
1972													
Temperature, °F	28.3	35.1	49.8	56.0	63.7	75.7	78.1	77.0	70.4	55.5	39.6	27.3	54.7
Precipitation, in.	0.14	0.06	0.82	1.93	6.87	3.36	3.47	5.60	2.94	1.02	3.86	1.02	31.09
1973													
Temperature, °F	28.9	35.8	47.1	52.5	62.4	75.9	80.3	79.6	66.5	60.9	45.5	31.0	55.5
Precipitation, in.	0.69	1.08	9.10	2.30	3.86	2.13	5.66	4.15	12.89	4.37	1.08	2.08	49.39
1974													
Temperature, °F	25.1	39.7	48.8	57.0	67.8	73.6	84.4	74.6	63.8	60.7	43.4	34.3	56.1
Precipitation, in.	0.14	0.03	1.50	4.20	9.06	2.68	0.70	4.69	0.31	3.89	0.68	0.57	28.45
1975													
Temperature, °F	32.5	29.2	38.2	54.9	65.3	73.0	79.6	81.3	65.9	60.7	44.5	36.6	55.1
Precipitation, in.	0.58	1.74	2.01	2.60	5.88	4.36	0.25	6.32	1.50	0.01	3.01	0.45	28.71

Thornthwaite Moisture Index:

1970	1971	1972	1973	1974	1975
-6.77	2.93	2.12	50.21	2.19	3.91

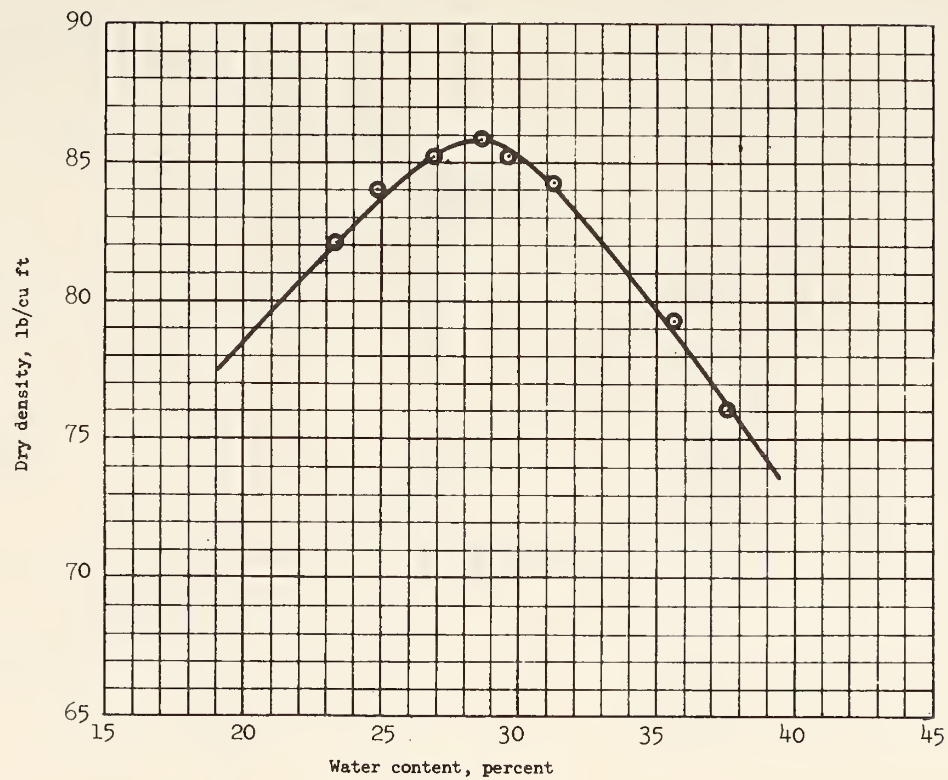
Avg = 9.1



GRADATION CURVE

SITE Ellsworth, Kans. BORING U-2

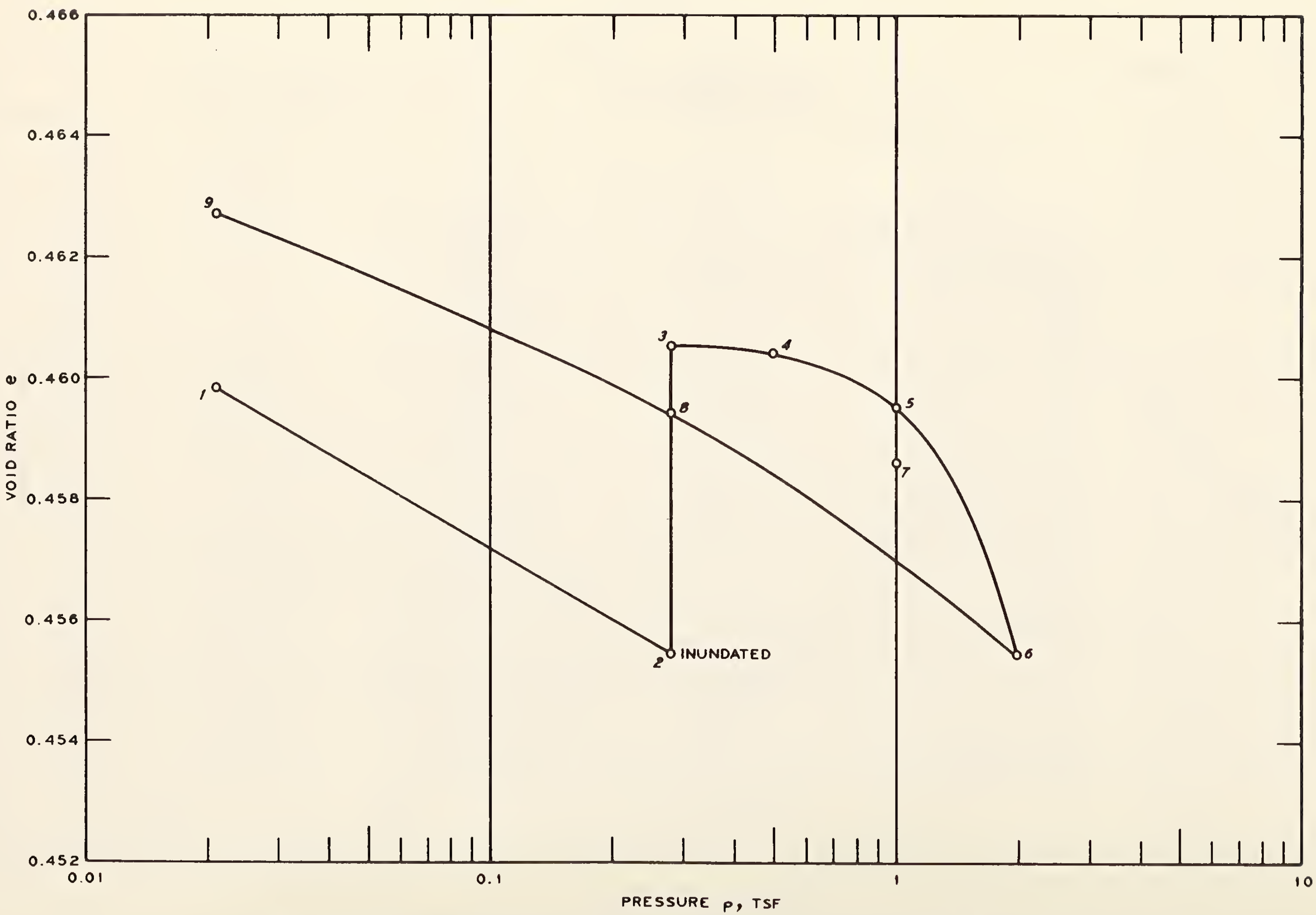
SAMPLE No. 1 DEPTH 2.0-4.3 ft



COMPACTION CURVE

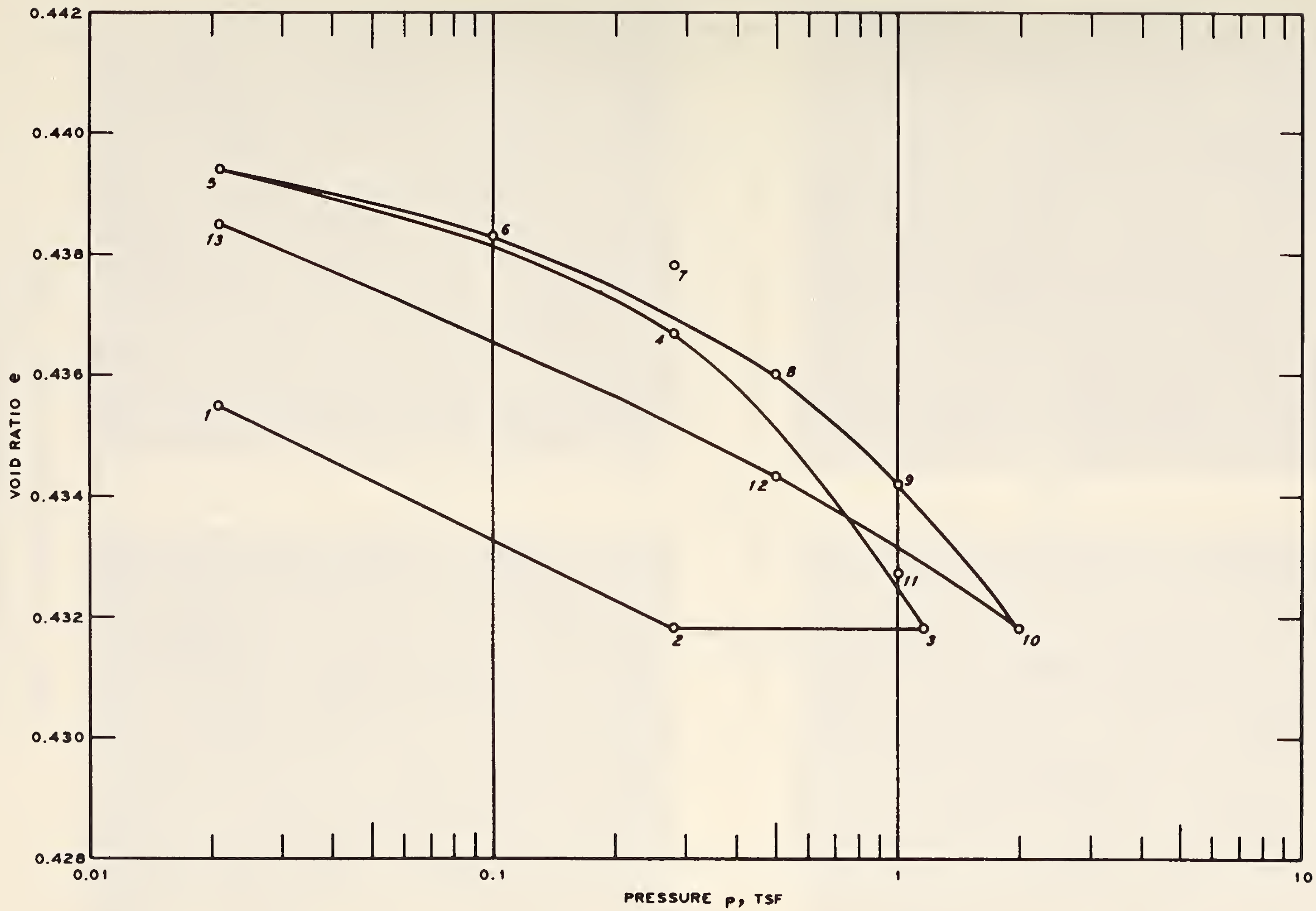
SITE Ellsworth, Kans.

SAMPLE Disturbed



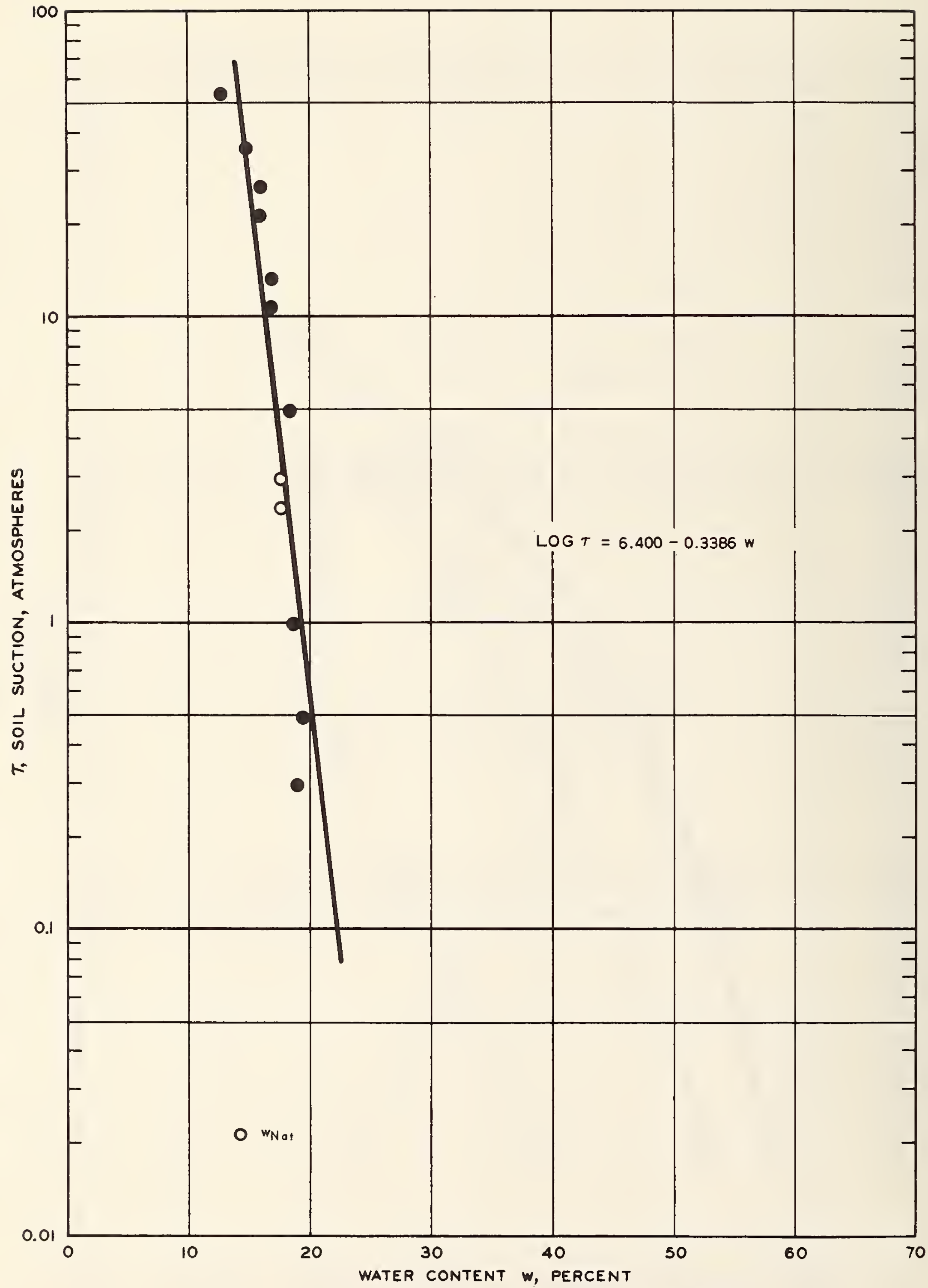
OVERBURDEN SWELL TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

SITE Ellsworth, Kans. BORING U-2 SAMPLE No. 1 DEPTH 2.0-4.3 ft



CONSTANT VOLUME SWELL PRESSURE TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

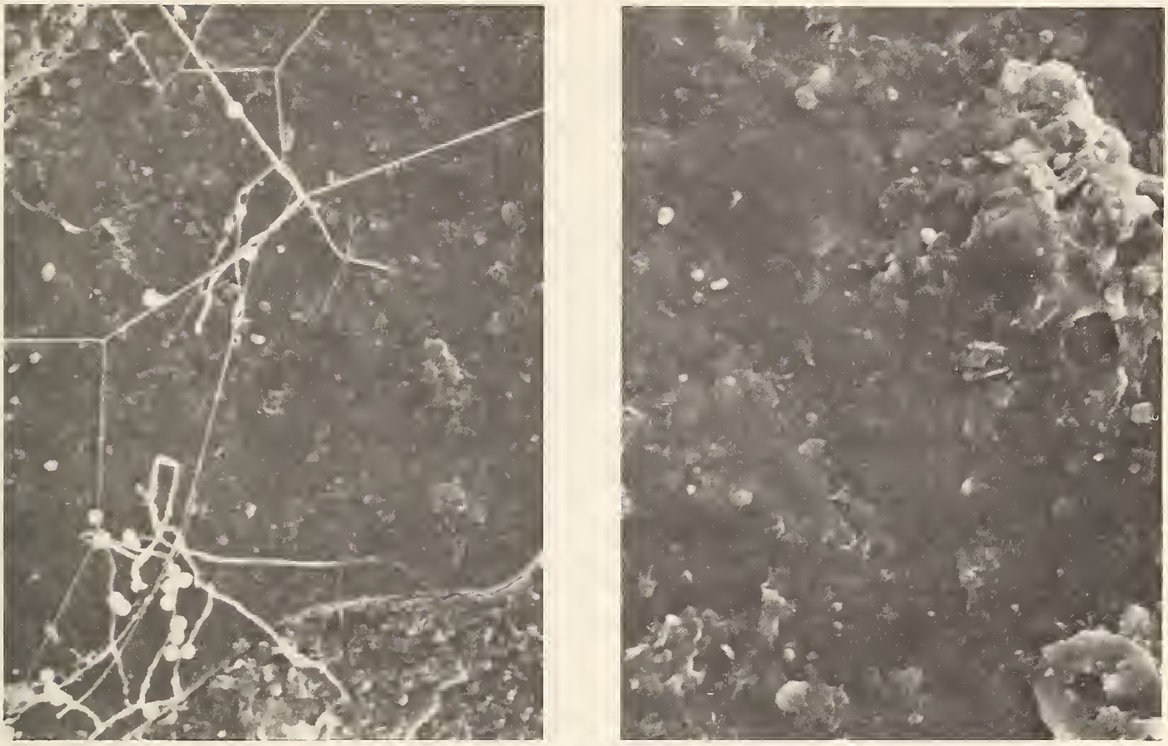
SITE <u>Ellsworth, Kans.</u> BORING <u>U-2</u> SAMPLE <u>No. 1</u> DEPTH <u>2.0-4.3 ft</u>



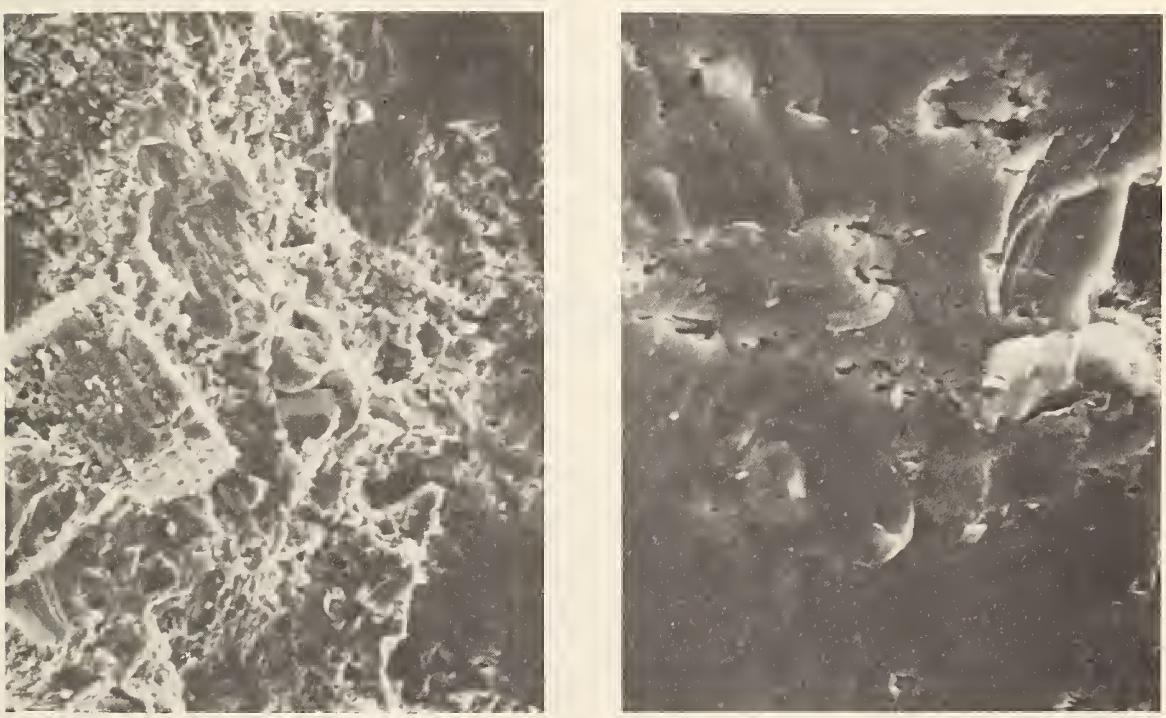
SOIL SUCTION VERSUS WATER CONTENT

SITE Ellsworth, Kans. BORING U-2

SAMPLE No. 1 DEPTH 2.0-4.3 ft



a. Normal to Y, ×650 and ×2300



10 μm

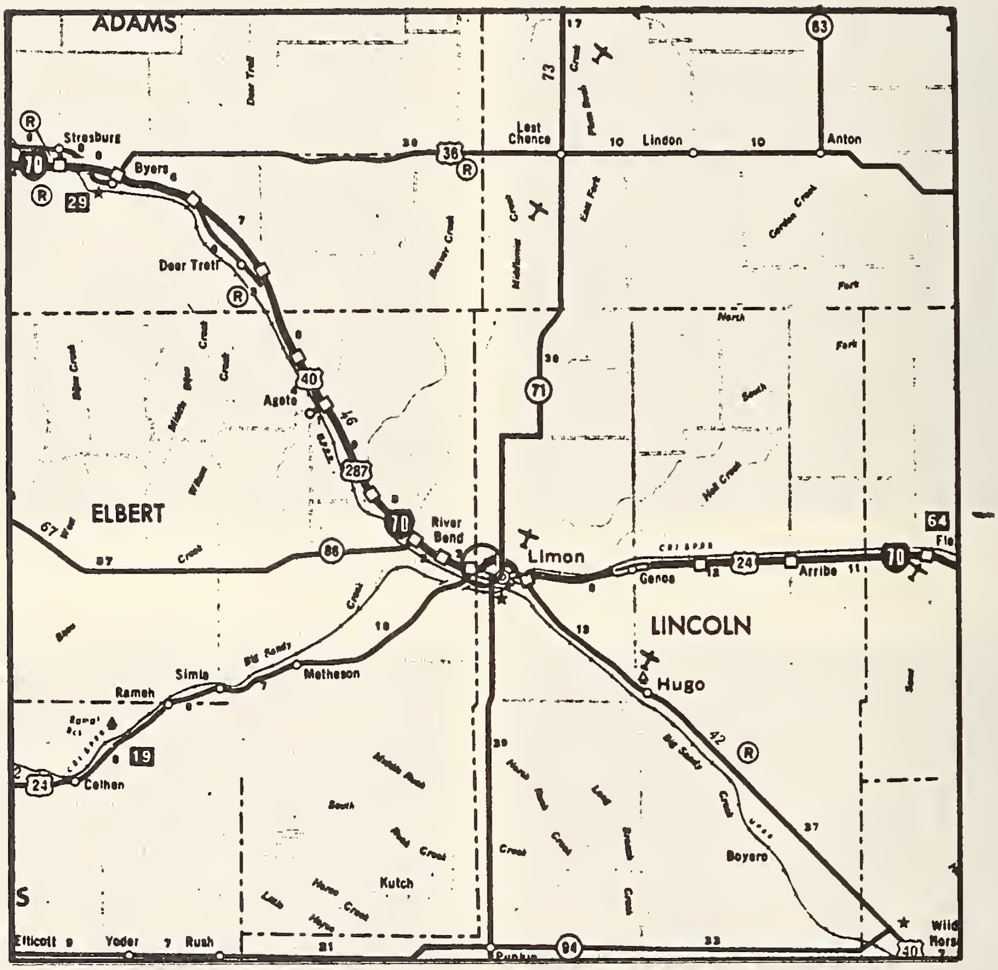
b. Normal to X, ×650 and ×2300

10 μm

SITE Ellsworth, Kans. BORING U-2

SAMPLE No. 1 DEPTH 2.0-4.3 ft

SAMPLING SITE NO. 14, LIMON, COLO.
(No. 1, I-70)



Site Location Information

157. Sampling site No. 14 is located in east-central Colorado approximately 3 miles west of Limon, Colo. The site is located approximately 0.5 mile east of I-70 and U. S. 24 junction on I-70. Samples were taken 33 ft north of the centerline of the westbound lane at station 152+00. Site is adjacent to Elbert-Lincoln County line.

Site Description

158. Sampling site is located in a moderate cut section (depth ≈ 15 to 20 ft) in open rolling terrain. Drainage is in a westerly

direction on a moderate to steep slope. Surrounding area has a partial grass cover and no trees.

Site Geology

159. Sampling site is located in the Colorado Piedmont Section of the Great Plains Physiographic Province. The topography is one of mature elevated plains exhibiting relatively low relief. Samples were taken from the Pierre Formation of the Montana Group, Gulfian Series, Cretaceous System. The Pierre Formation is predominantly shale interbedded with considerable sandstone. The thickness of the Pierre varies and may exceed 1000 ft. The Pierre is underlain by the Niobrara Formation and overlies the Fox Hill sandstone. The Pierre exhibits a relatively extensive outcrop area in east-central and northeastern Colorado.

Sample Description

160. The Pierre Formation as sampled near Limon, Colo., is a moderately hard, indurated, weathered, calcareous olive gray (5 Y 6/1) silty shale. Bedding planes are moderately developed in the less weathered materials and not apparent in highly weathered samples. Material contains accessory mica and small carbonaceous fragments ($\approx$ 1-mm diam). Cracks are present along bedding planes and occasional circular voids are present. The SEM photographs show a moderate face-to-face particle orientation with wavey stratifications.

Description of Climate

161. Most of Colorado has a cool and invigorating climate which could be termed a highland or mountain climate of a continental location. During summer there are hot days in the plains, but these are often relieved by afternoon thundershowers. Mountain regions are nearly always cool. Humidity is generally quite low; this favors rapid evaporation and a relatively comfortable feeling even on hot days. The thin atmosphere allows greater penetration of solar radiation and results in pleasant daytime conditions even during the winter. This is why skiers at high elevations are often pictured in very light clothing, although surrounded by heavy snow.

162. The climates of local areas are profoundly affected by differences in elevation, and to a lesser degree, by the orientation of

mountain ranges and valleys with respect to general air movements. Wide variations occur within short distances. The difference (35°F) in annual mean temperature between Pikes Peak and Las Animas, 90 miles to the southeast, is about the same as that between southern Florida and Iceland. The average annual snowfall at Cumbres in the southern mountains is nearly 300 in.; less than 30 miles away at Manassa in the San Luis Valley, snowfall is less than 25 in. While temperature decreases, and precipitation generally increases with altitude, these patterns are modified by the orientation of mountain slopes with respect to the prevailing winds and by the effect of topographical features in creating local air movements.

163. As a result of the State's distance from major sources of moisture (the Pacific Ocean and the Gulf of Mexico), precipitation is generally light in the lower elevations. Prevailing air currents reach Colorado from westerly directions. Eastward-moving storms originating in the Pacific Ocean lose much of their moisture in passage over mountain ranges to the west; a large part of the remaining moisture falls as rain or snow on the mountaintops and westward-facing slopes. Eastern slope areas receive relatively small amounts of precipitation from these storms.

164. The climate of the plains is comparatively uniform from place to place, with characteristic features of low relative humidity, abundant sunshine, light rainfall, moderate to high wind movement, and a large daily range in temperature. Summer daily maximum temperatures are often 95°F or above, and 100°F temperatures have been observed at all plains stations. Such temperatures are not infrequent at altitudes below 5000 ft; above that elevation they are comparatively rare. The highest official temperature on record in Colorado occurred at Bennett, in the northeastern plains, where 118°F was recorded on July 11, 1888. Because of the very low relative humidity accompanying these high temperatures, hot days cause less discomfort than in more humid areas. The usual winter extremes in the plains are from zero to 10°F or 15°F below zero.

165. An important feature of the precipitation in the plains is the large proportion of the annual total which falls in the growing

season--70 to 80 percent during the period from April through September. Summer precipitation in the plains is largely from thunderstorm activity and is sometimes extremely heavy. Strong winds occur frequently in winter and spring. These winds tend to dry out soils, which are not well supplied with moisture because of the low annual precipitation. During periods of drought such winds give rise to the dust storms which are especially characteristic of the southeastern plains.

166. At the western edge of the plains and near the foothills of the mountains, there are a number of significant changes in climate as compared to the plains proper. Average wind movement is less, but areas very near the mountains are subject to periodic, severe turbulent winds from the effects of mountain waves generated by the flow of high westerly winds over the mountain barrier. Temperature changes from day to day are not as great; summer temperatures are lower, and winter temperatures are higher. Precipitation, which decreases gradually from the eastern border to a minimum near the mountains, increases rapidly with the increasing elevation of the foothills and proximity to the higher ranges. The decrease in temperature from the eastern boundary westward to the foothills is less than might be expected with increasing altitude. This results from mountain and valley winds and greater frequency of the Chinook. Below the Royal Gorge, the mountain and valley winds are strong enough to modify the climate of a considerable area. Descending air currents frequently prevent the stratification of air necessary for the occurrence of excessive cold. As a consequence, the winter climate is milder than elsewhere in the State.

167. The rugged topography of western Colorado causes large variations in climate within short distances, and few climatic generalizations apply to the whole area. At the summits of mountains, temperatures are low, averaging less than 32°F over the year. Snow-covered mountain parks and valleys often have very cold nighttime temperatures in winter, when skies are clear and the air is still--occasionally to 50°F below zero. The record official low temperature in Colorado is 60°F below zero at Taylor Park Dam (at an elevation of about 9200 ft) in the high country north of Gunnison, on February 1, 1951. Summer in

the mountains is a cool and refreshing season. At typical mountain stations the average July temperature is in the neighborhood of 60°F. The highest temperatures are usually in the seventies and eighties, but may reach 90 to 95°F. Above 7000 ft, the nights are quite cool throughout the summer, while bright sunshine makes the days confortably warm.

168. The lower western valleys of the State are protected by surrounding high terrain, and have a greater uniformity of weather than the eastern plains. They experience high summer temperatures, comparable to those of the eastern plains, while average winter temperatures are somewhat lower than at similar elevations in the plains, due largely to the relative infrequency of Chinook or other warming winds.

169. Precipitation west of the Continental Divide is more evenly distributed throughout the year than in the eastern plains. For most of western Colorado, the greatest monthly precipitation occurs in the winter months, while June is the driest month. In contrast, June is one of the wetter months in most of the eastern part of the State.

Climatic Data Summary

Reporting Station: Limon 10 SSW (05-5015-01) for 1941-70
Limon WSMO (05-5018-01) for 1971-75

Mean Monthly Temperature and Normal
Monthly Precipitation for Period 1941-70:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature, °F	27.7	30.7	34.8	46.0	55.6	64.9	71.4	69.9	61.5	50.8	37.2	30.5	48.4
Precipitation, in.	0.41	0.33	0.89	1.28	2.47	2.08	2.64	2.57	1.20	0.86	0.57	0.26	15.56

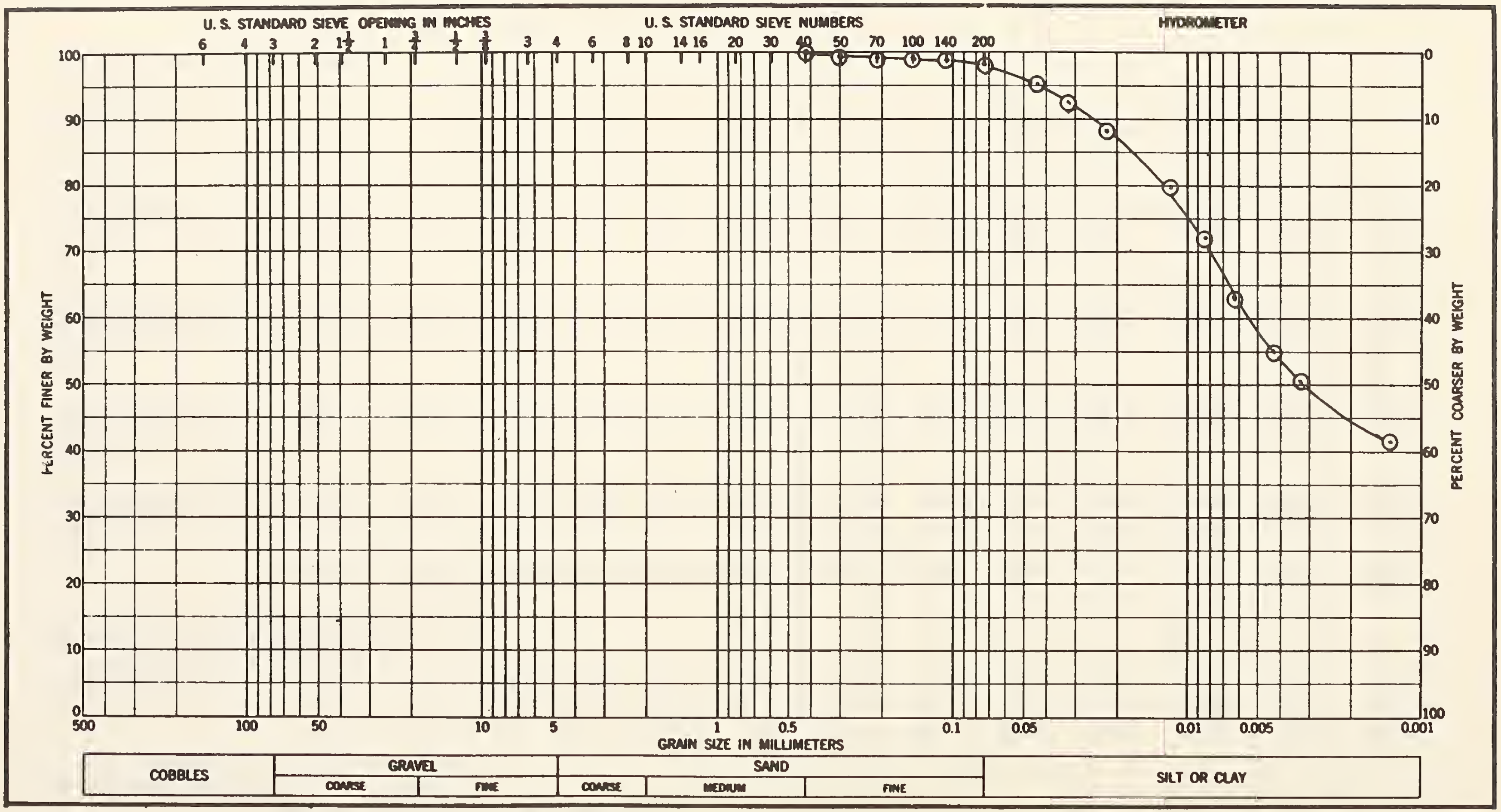
Average Monthly Temperature and
Total Monthly Precipitation for 1971-75:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1971													
Temperature, °F	27.3	27.4	34.2	43.8	51.4	67.4	68.2	69.2	55.8	47.4	36.6	29.3	46.5
Precipitation, in.	0.35	0.35	0.44	2.40	1.41	1.09	2.27	0.63	1.55	0.58	0.08	0.11	11.26
1972													
Temperature, °F	26.1	32.5	40.6	46.1	53.1	66.5	67.8	66.8	59.3	47.2	27.2	19.4	46.1
Precipitation, in.	0.15	0.09	0.47	0.77	1.74	3.17	3.10	1.87	1.91	0.65	0.95	0.24	15.11
1973													
Temperature, °F	22.7	31.0	34.2	38.8	51.9	64.1	67.8	70.0	57.5	50.9	37.6	27.7	46.2
Precipitation, in.	0.37	0.03	1.25	1.83	3.67	1.99	5.05	0.79	1.20	0.22	0.11	0.56	17.07
1974													
Temperature, °F	22.8	31.6	39.5	44.5	57.0	64.7	71.9	65.9	56.3	50.1	34.9	26.0	47.1
Precipitation, in.	0.11	0.08	1.09	0.65	0.32	1.61	2.42	2.14	0.44	0.69	0.38	0.10	10.03
1975													
Temperature, °F	--*	--*	--*	--*	--*	--*	--*	--*	57.8	50.0	32.1	32.1	--
Precipitation, in.	--*	--*	--*	--*	--*	--*	--*	--*	0.16	0.21	0.64	0.07	--

Thornthwaite Moisture Index:

1970	1971	1972	1973	1974	1975	
-8.41	-19.74	-26.07	-5.29	-22.40	-18.89	Avg = -16.8

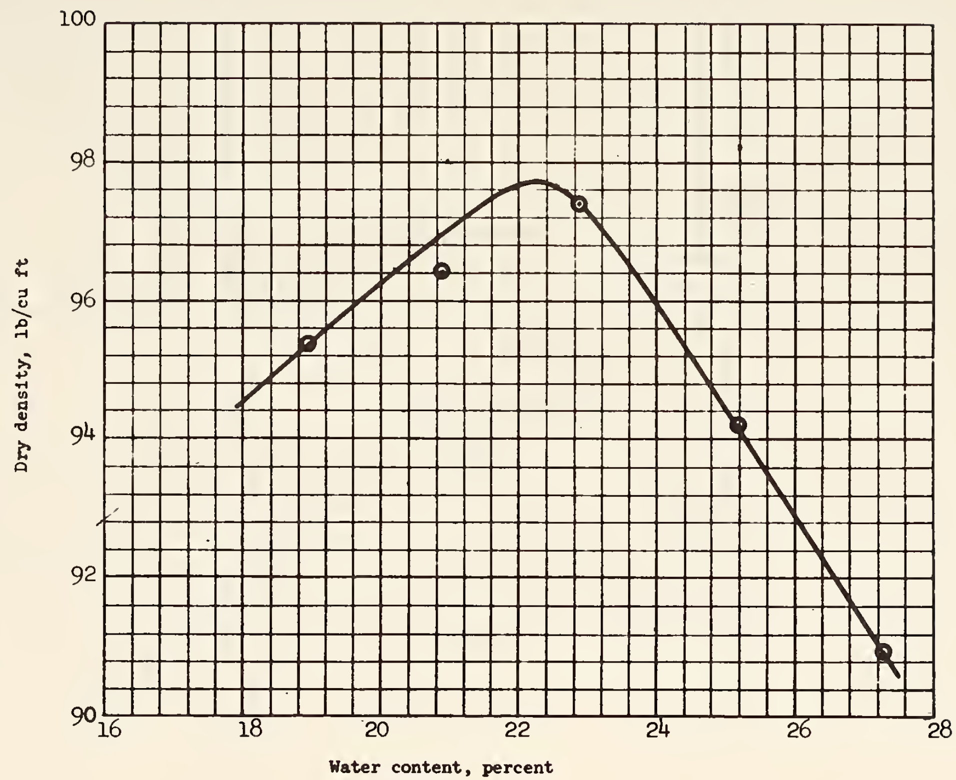
* Record missing.



GRADATION CURVE

SITE Limon, Colo. (No. 1, I-70) BORING U-1

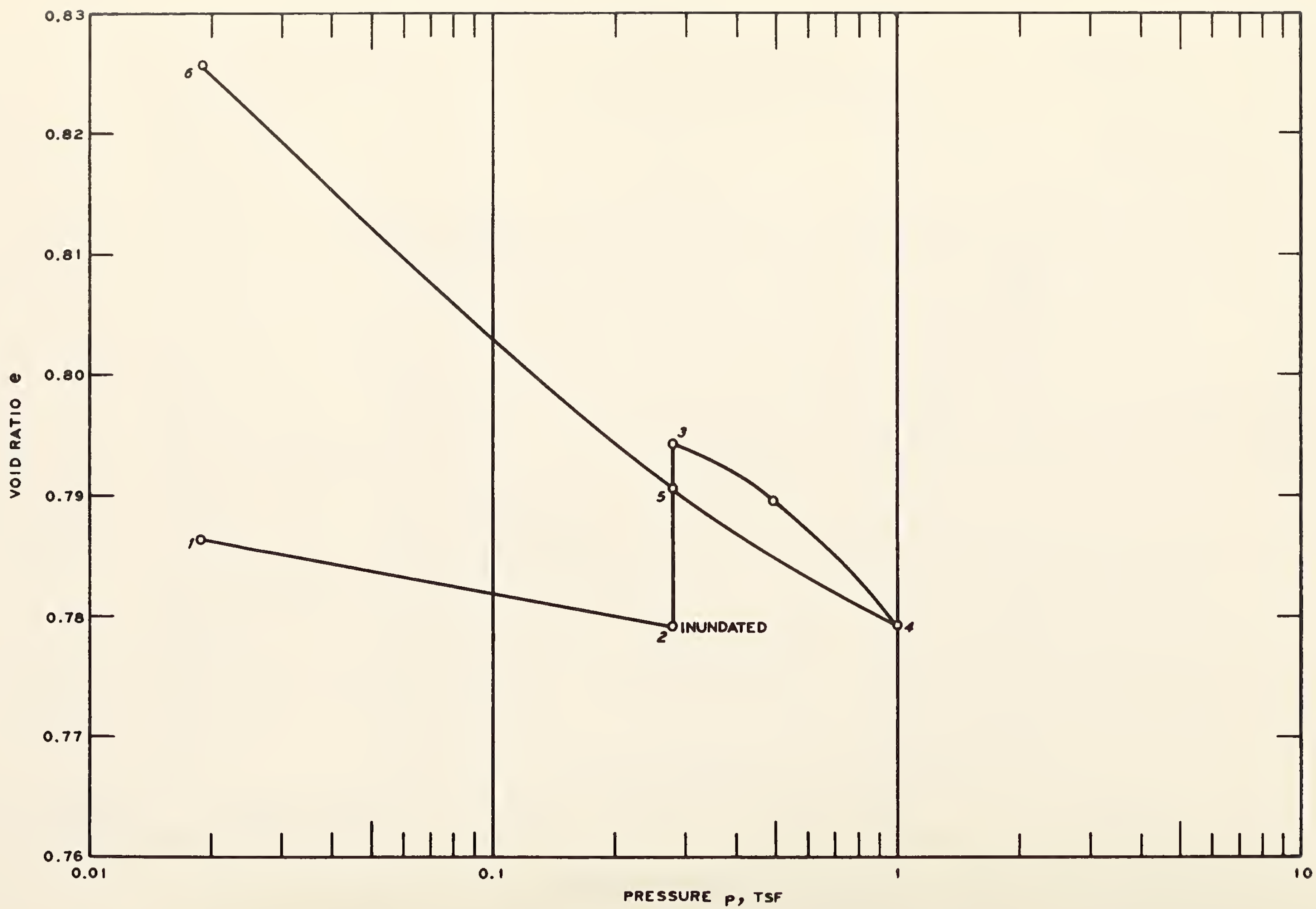
SAMPLE No. 5 DEPTH 4.2-6.3 ft



COMPACTION CURVE

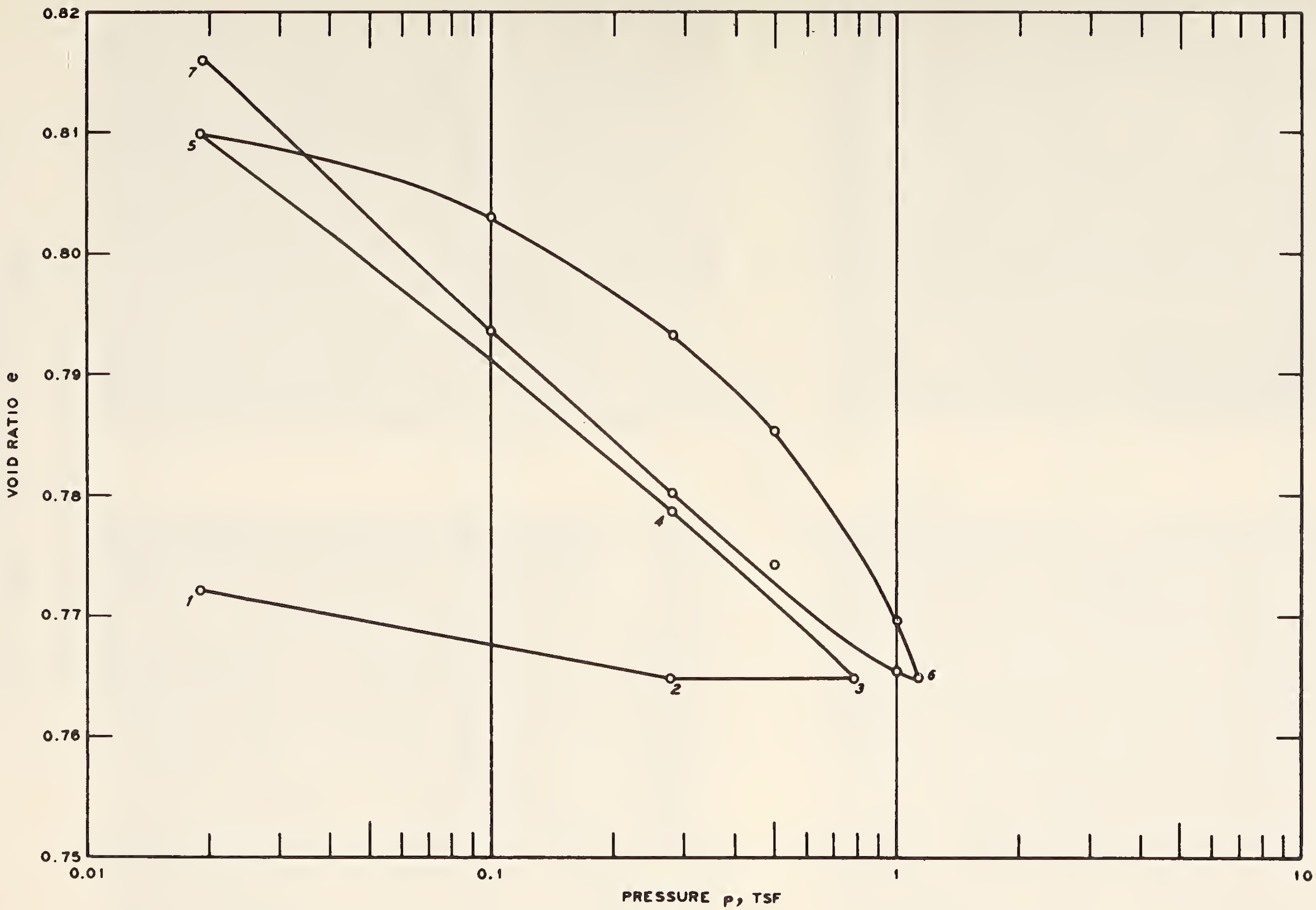
SITE Limon, Colo. (No. 1, I-70)

SAMPLE Disturbed



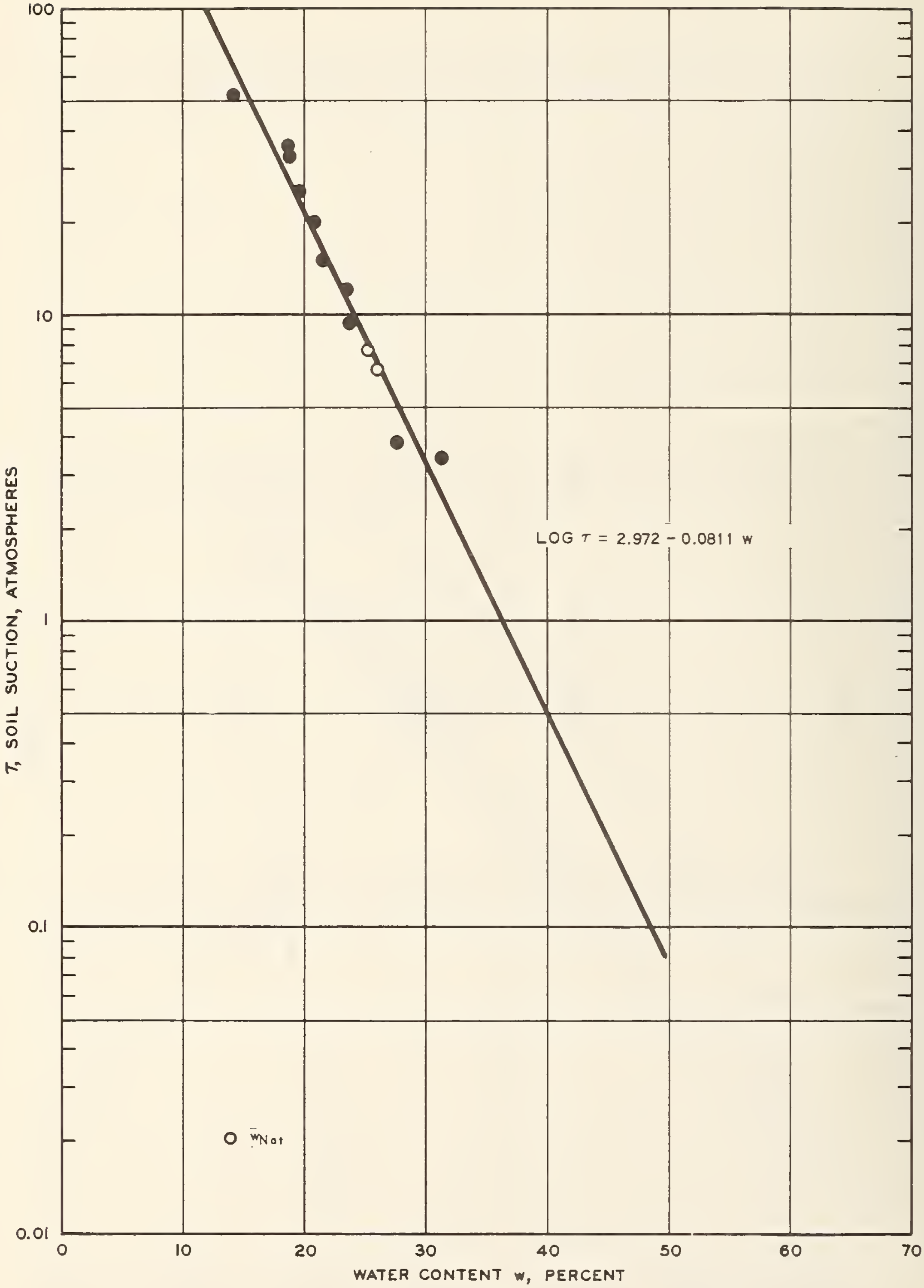
OVERBURDEN SWELL TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

SITE Limon, Colo. (No. 1, I-70) BORING U-1 SAMPLE No. 5 DEPTH 4.2-6.3 ft



CONSTANT VOLUME SWELL PRESSURE TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

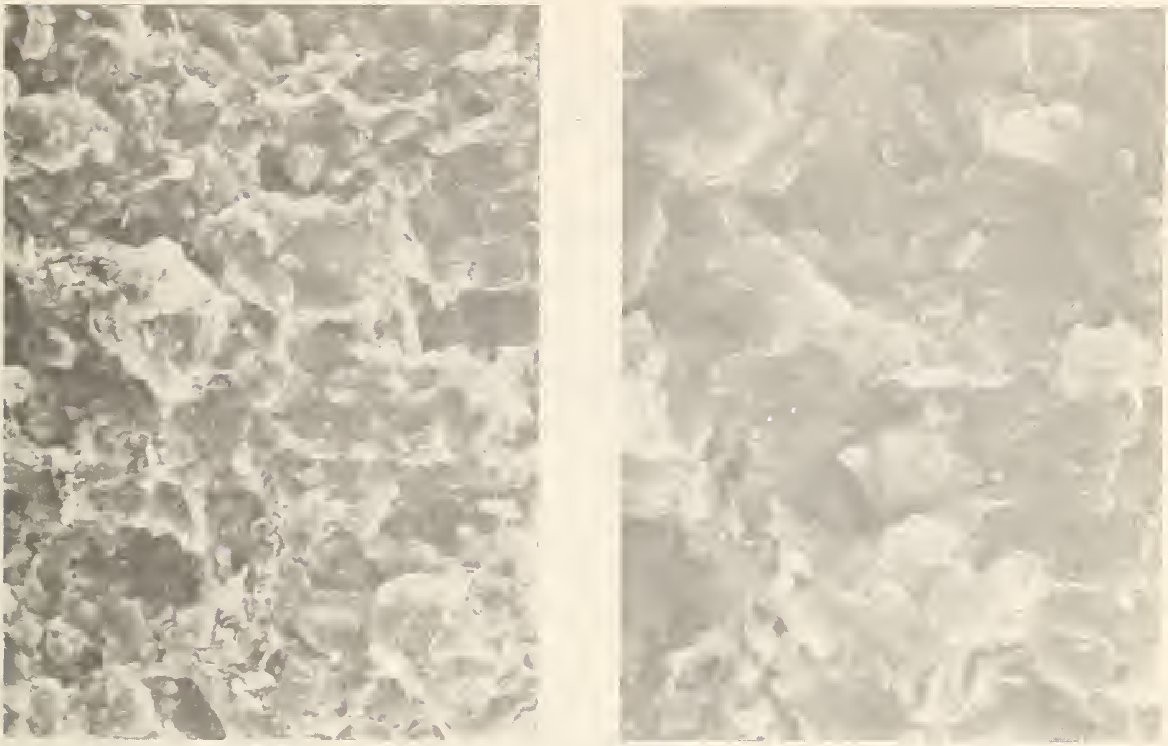
SITE Limon, Colo. (No. 1, I-70) BORING U-1 SAMPLE No. 5 DEPTH 4.2-6.3 ft



SOIL SUCTION VERSUS WATER CONTENT

SITE Limon, Colo. (No. 1, I-70) BORING U-1

SAMPLE No. 5 DEPTH 4.2-6.3 ft



a. Normal to Y, ×650 and ×2300

10 μm

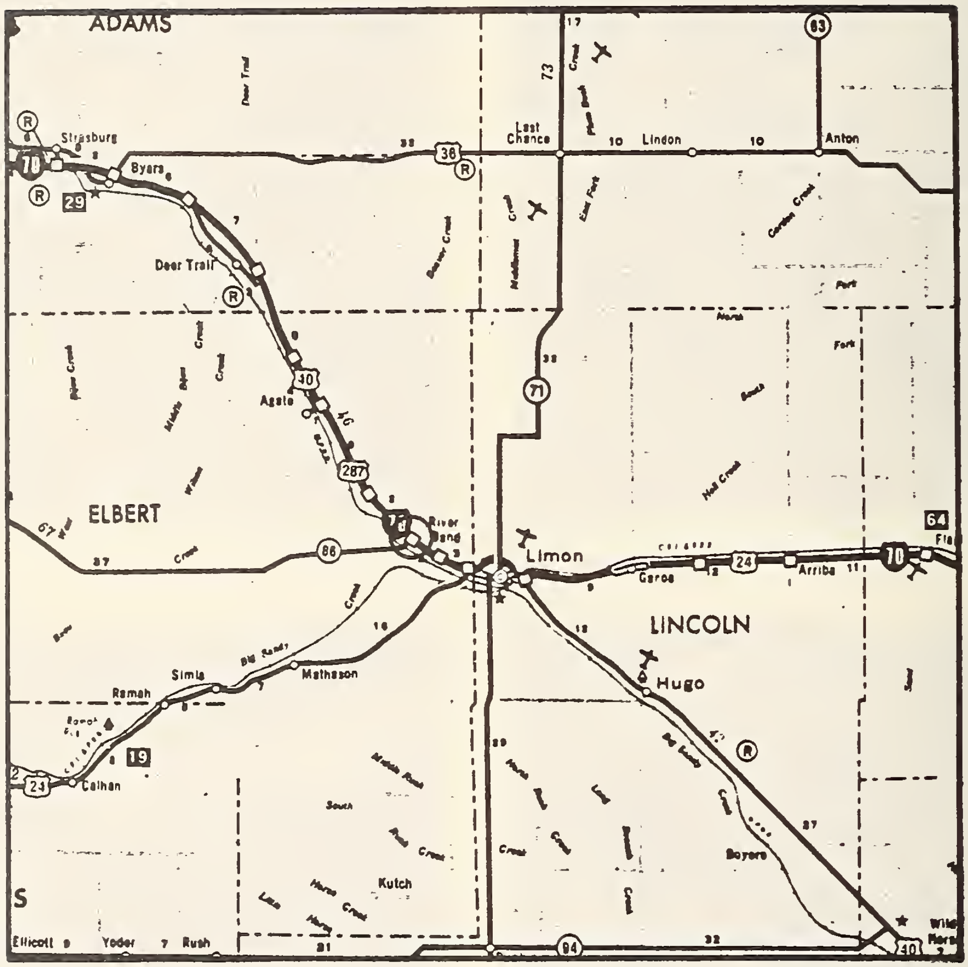
b. Normal to X, ×650 and ×2300

10 μm

SITE Limon, Colo., (No. 1, I-70) BORING U-1

SAMPLE No. 5 DEPTH 4.2-6.3 ft

SAMPLING SITE NO. 15, LIMON, COLO.
(No. 2, I-70)



Site Location Information

170. Sampling site No. 15 is located in east-central Colorado approximately 10 miles west of Limon, Colo. The site is located approximately 0.5 mile west of I-70 and SH 86 west junction on I-70. Samples were taken in north verge slope (22 ft north of centerline) of westbound lane adjacent to junction of on-ramp with I-70; approximately 1300 west of ramp No. 96.

Site Description

171. Sampling site is located in a shallow cut-grade section

(depth $\approx$ 3 to 5 ft) in open rolling terrain. Drainage is in an easterly direction on a moderate slope. Surrounding area has a partial grass cover and no trees.

Site Geology

172. Sampling site is located in the Colorado Piedmont Section of the Great Plains Physiographic Province. The relief is relatively low and rolling with the topographic characteristics of mature elevated plains. Samples were taken from the Laramie Formation of the Upper Series of the Cretaceous System. The Laramie Formation consists of approximately 375 ft (maximum) of sandstone, shale, tuff, and coal overlying the Fox Hill sandstone and underlying the Denver Formation with a major outcrop in east-central Colorado.

Sample Description

173. The Laramie Formation as sampled near Limon, Colo., is a hard, indurated, slightly weathered, noncalcareous, gray (N3) to grayish black (N2) silty shale. The Laramie exhibits well-developed stratification, abundant coal fragments (up to 2 cm), and voids and open cracks, particularly in the more weathered fragments. The SEM photographs indicate a well-developed, face-to-face particle orientation with abundant microfractures.

Description of Climate

174. Most of Colorado has a cool and invigorating climate which could be termed a highland or mountain climate of a continental location. During summer there are hot days in the plains, but these are often relieved by afternoon thundershowers. Mountain regions are nearly always cool. Humidity is generally quite low; this favors rapid evaporation and a relatively comfortable feeling even on hot days. The thin atmosphere allows greater penetration of solar radiation and results in pleasant daytime conditions even during the winter. This is why skiers at high elevations are often pictured in very light clothing, although surrounded by heavy snow.

175. The climates of local areas are profoundly affected by differences in elevation, and to a lesser degree, by the orientation of mountain ranges and valleys with respect to general air movements. Wide

variations occur within short distances. The difference (35°F) in annual mean temperature between Pikes Peak and Las Animas, 90 miles to the southeast, is about the same as that between southern Florida and Iceland. The average annual snowfall at Cumbres in the southern mountains is nearly 300 in.; less than 30 miles away at Manassa in the San Luis Valley, snowfall is less than 25 in. While temperature decreases, and precipitation generally increases with altitude, these patterns are modified by the orientation of mountain slopes with respect to the prevailing winds and by the effect of topographical features in creating local air movements.

176. As a result of the State's distance from major sources of moisture (the Pacific Ocean and the Gulf of Mexico), precipitation is generally light in the lower elevations. Prevailing air currents reach Colorado from westerly directions. Eastward-moving storms originating in the Pacific Ocean lose much of their mositure in passage over mountain ranges to the west; a large part of the remaining moisture falls as rain or snow on the mountaintops and westward-facing slopes. Eastern slope areas receive relatively small amounts of precipitation from these storms.

177. The climate of the plains is comparatively uniform from place to place, with characteristic features of low relative humidity, abundant sunshine, light rainfall, moderate to high wind movement, and a large daily range in temperature. Summer daily maximum temperatures are often 95°F or above, and 100°F temperatures have been observed at all plains stations. Such temperatures are not infrequent at altitudes below 5000 ft; above that elevation they are comparatively rare. The highest official temperature on record in Colorado occurred at Bennett, in the northeastern plains, where 118°F was recorded on July 11, 1888. Because of the very low relative humidity accompanying these high temperatures, hot days cause less discomfort than in more humid areas. The usual winter extremes in the plains are from zero to 10°F or 15°F below zero.

178. An important feature of the precipitation in the plains is the large proportion of the annual total which falls in the growing season--70 to 80 percent during the period from April through September.

Summer precipitation in the plains is largely from thunderstorm activity and is sometimes extremely heavy. Strong winds occur frequently in winter and spring. These winds tend to dry out soils, which are not well supplied with moisture because of the low annual precipitation. During periods of drought such winds give rise to the dust storms which are especially characteristic of the southeastern plains.

179. At the western edge of the plains and near the foothills of the mountains, there are a number of significant changes in climate as compared to the plains proper. Average wind movement is less, but areas very near the mountains are subject to periodic, severe turbulent winds from the effects of mountain waves generated by the flow of high westerly winds over the mountain barrier. Temperature changes from day to day are not as great; summer temperatures are lower, and winter temperatures are higher. Precipitation, which decreases gradually from the eastern border to a minimum near the mountains, increases rapidly with the increasing elevation of the foothills and proximity to the higher ranges. The decrease in temperature from the eastern boundary westward to the foothills is less than might be expected with increasing altitude. This results from mountain and valley winds and greater frequency of the Chinook. Below the Royal Gorge, the mountain and valley winds are strong enough to modify the climate of a considerable area. Descending air currents frequently prevent the stratification of air necessary for the occurrence of excessive cold. As a consequence, the winter climate is milder than elsewhere in the State.

180. The rugged topography of western Colorado causes large variations in climate within short distances, and few climatic generalizations apply to the whole area. At the summits of mountains, temperatures are low, averaging less than 32°F over the year. Snow-covered mountain parks and valleys often have very cold nighttime temperatures in winter, when skies are clear and the air is still--occasionally to 50°F below zero. The record official low temperature in Colorado is 60°F below zero at Taylor Park Dam (at an elevation of about 9200 ft) in the high country north of Gunnison, on February 1, 1951. Summer in the mountains is a cool and refreshing season. At typical mountain

stations the average July temperature is in the neighborhood of 60°F. The highest temperatures are usually in the seventies and eighties, but may reach 90 to 95°F. Above 7000 ft, the nights are quite cool throughout the summer, while bright sunshine makes the days confortably warm.

181. The lower western valleys of the State are protected by surrounding high terrain, and have a greater uniformity of weather than the eastern plains. They experience high summer temperatures, comparable to those of the eastern plains, while average winter temperatures are somewhat lower than at similar elevations in the plains, due largely to the relative infrequency of Chinook or other warming winds.

182. Precipitation west of the Continental Divide is more evenly distributed throughout the year than in the eastern plains. For most of western Colorado, the greatest monthly precipitation occurs in the winter months, while June is the driest month. In contrast, June is one of the wetter months in most of the eastern part of the State.

Climatic Data Summary

Reporting Station: Limon 10 SSW (05-5015-01) for 1941-70
Limon WSMO (05-5018-01) for 1971-75

Mean Monthly Temperature and Normal
Monthly Precipitation for Period 1941-70:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature, °F	27.7	30.7	34.8	46.0	55.6	64.9	71.4	69.9	61.5	50.8	37.2	30.5	48.4
Precipitation, in.	0.41	0.33	0.89	1.28	2.47	2.08	2.64	2.57	1.20	0.86	0.57	0.26	15.56

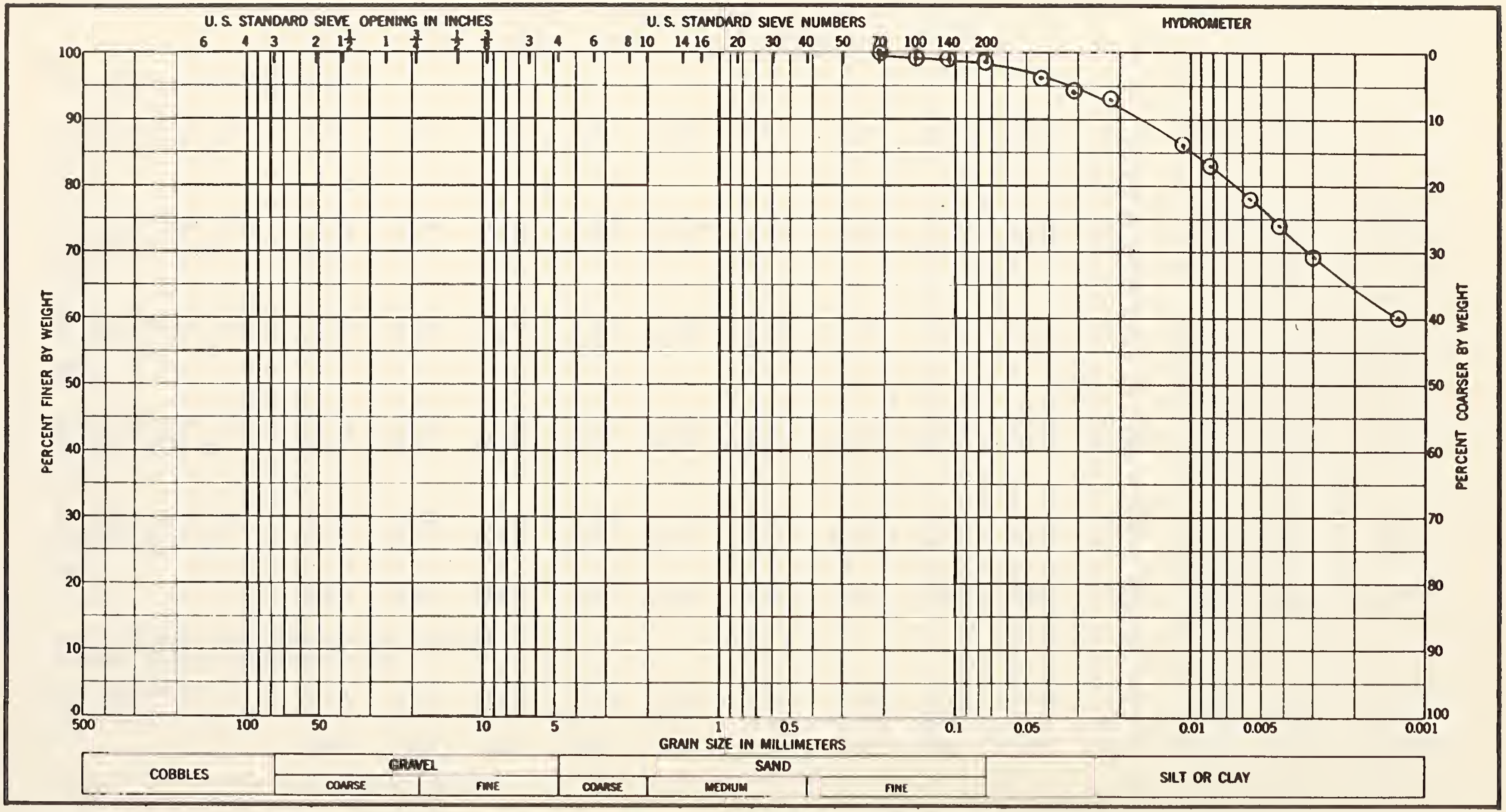
Average Monthly Temperature and
Total Monthly Precipitation for 1971-75:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1971													
Temperature, °F	27.3	27.4	34.2	43.8	51.4	67.4	68.2	69.2	55.8	47.4	36.6	29.3	46.5
Precipitation, in.	0.35	0.35	0.44	2.40	1.41	1.09	2.27	0.63	1.55	0.58	0.08	0.11	11.26
1972													
Temperature, °F	26.1	32.5	40.6	46.1	53.1	66.5	67.8	66.8	59.3	47.2	27.2	19.4	46.1
Precipitation, in.	0.15	0.09	0.47	0.77	1.74	3.17	3.10	1.87	1.91	0.65	0.95	0.24	15.11
1973													
Temperature, °F	22.7	31.0	34.2	38.8	51.9	64.1	67.8	70.0	57.5	50.9	37.6	27.7	46.2
Precipitation, in.	0.37	0.03	1.25	1.83	3.67	1.99	5.05	0.79	1.20	0.22	0.11	0.56	17.07
1974													
Temperature, °F	22.8	31.6	39.5	44.5	57.0	64.7	71.9	65.9	56.3	50.1	34.9	26.0	47.1
Precipitation, in.	0.11	0.08	1.09	0.65	0.32	1.61	2.42	2.14	0.44	0.69	0.38	0.10	10.03
1975													
Temperature, °F	--*	--*	--*	--*	--*	--*	--*	--*	57.8	50.0	32.1	32.1	--
Precipitation, in.	--*	--*	--*	--*	--*	--*	--*	--*	0.16	0.21	0.64	0.07	--

Thornthwaite Moisture Index:

1970	1971	1972	1973	1974	1975	
-8.41	-19.74	-26.07	-5.29	-22.40	-18.89	Avg = -16.8

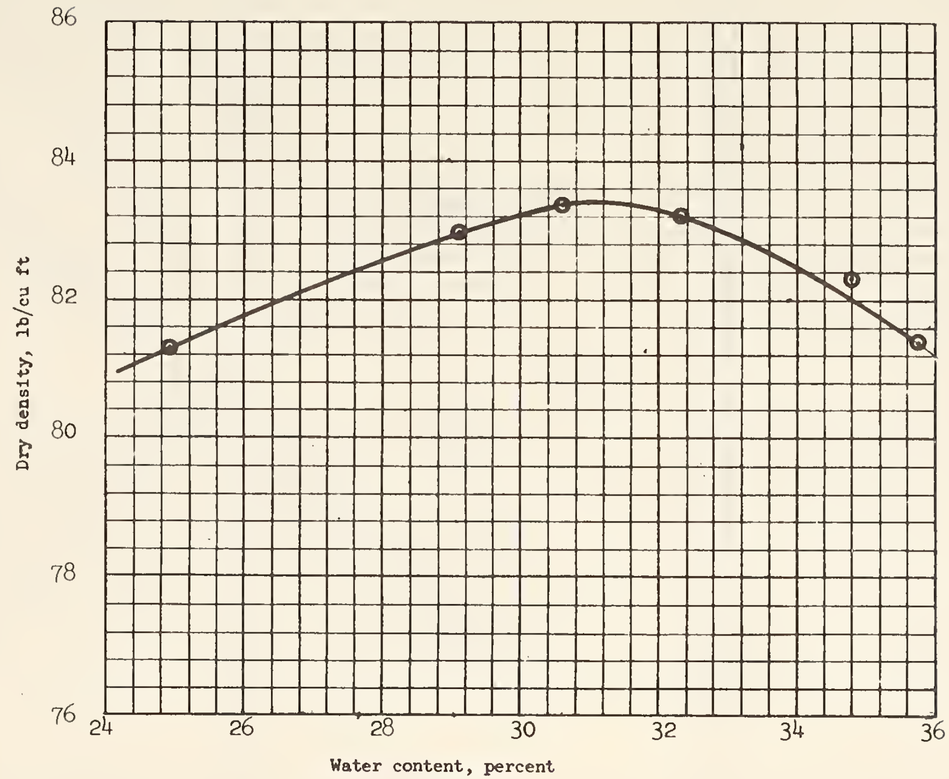
* Record missing.



GRADATION CURVE

SITE Limon, Colo. (No. 2, I-70) BORING U-1

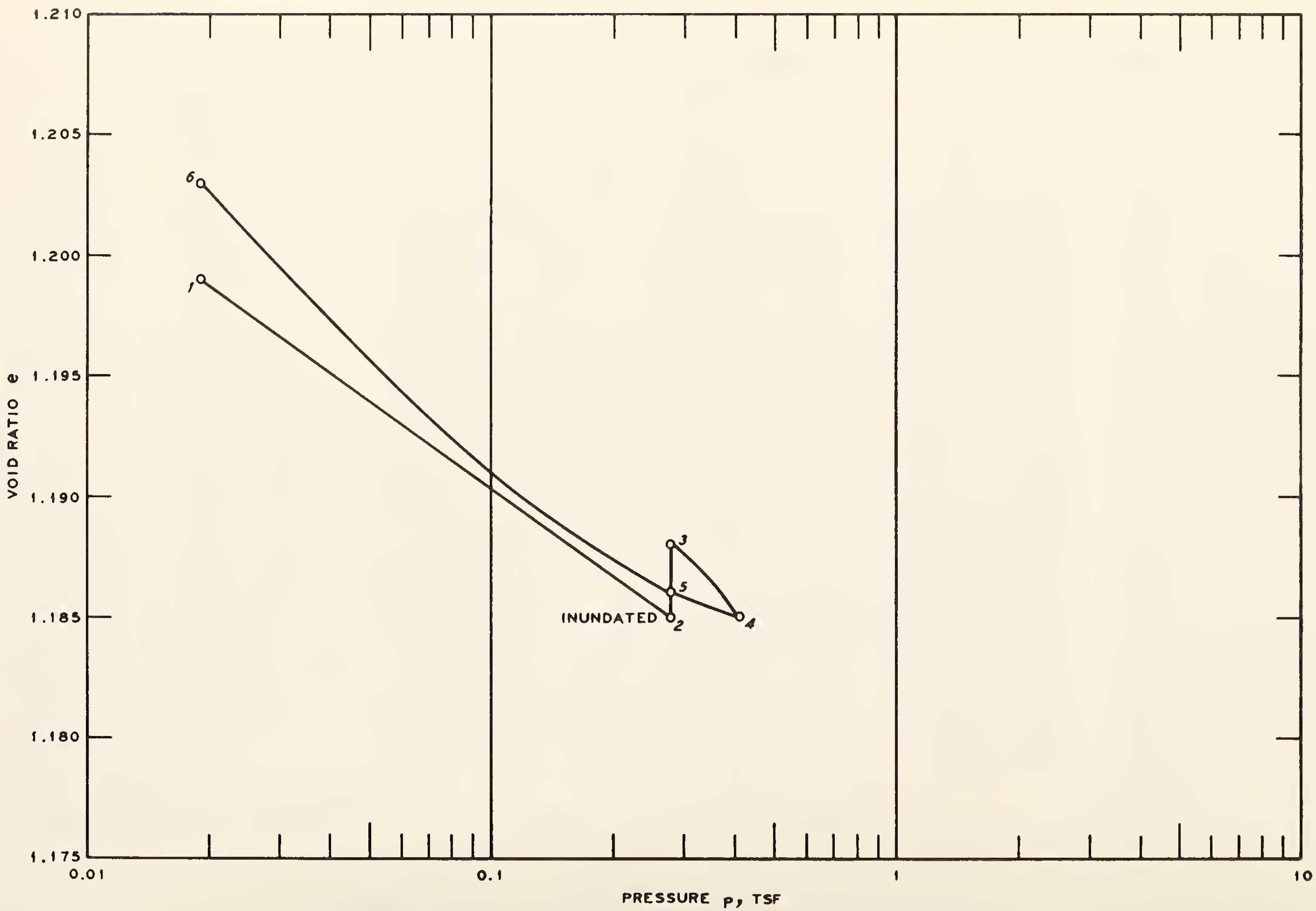
SAMPLE No. 1 DEPTH 3.4-5.0 ft



COMPACTION CURVE

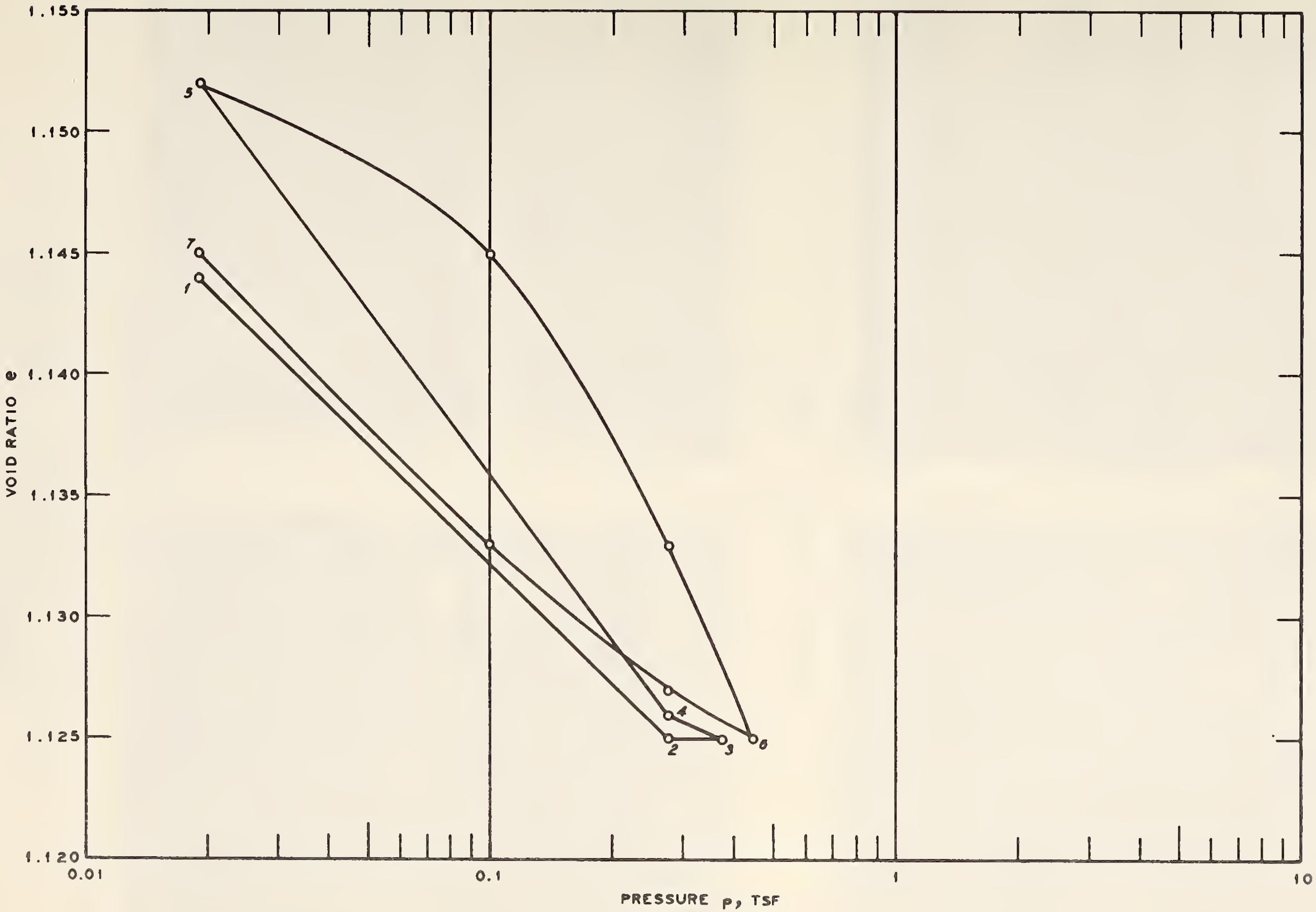
SITE <u>Limon, Colo. (No. 2, I-70)</u>

SAMPLE <u>Disturbed</u>



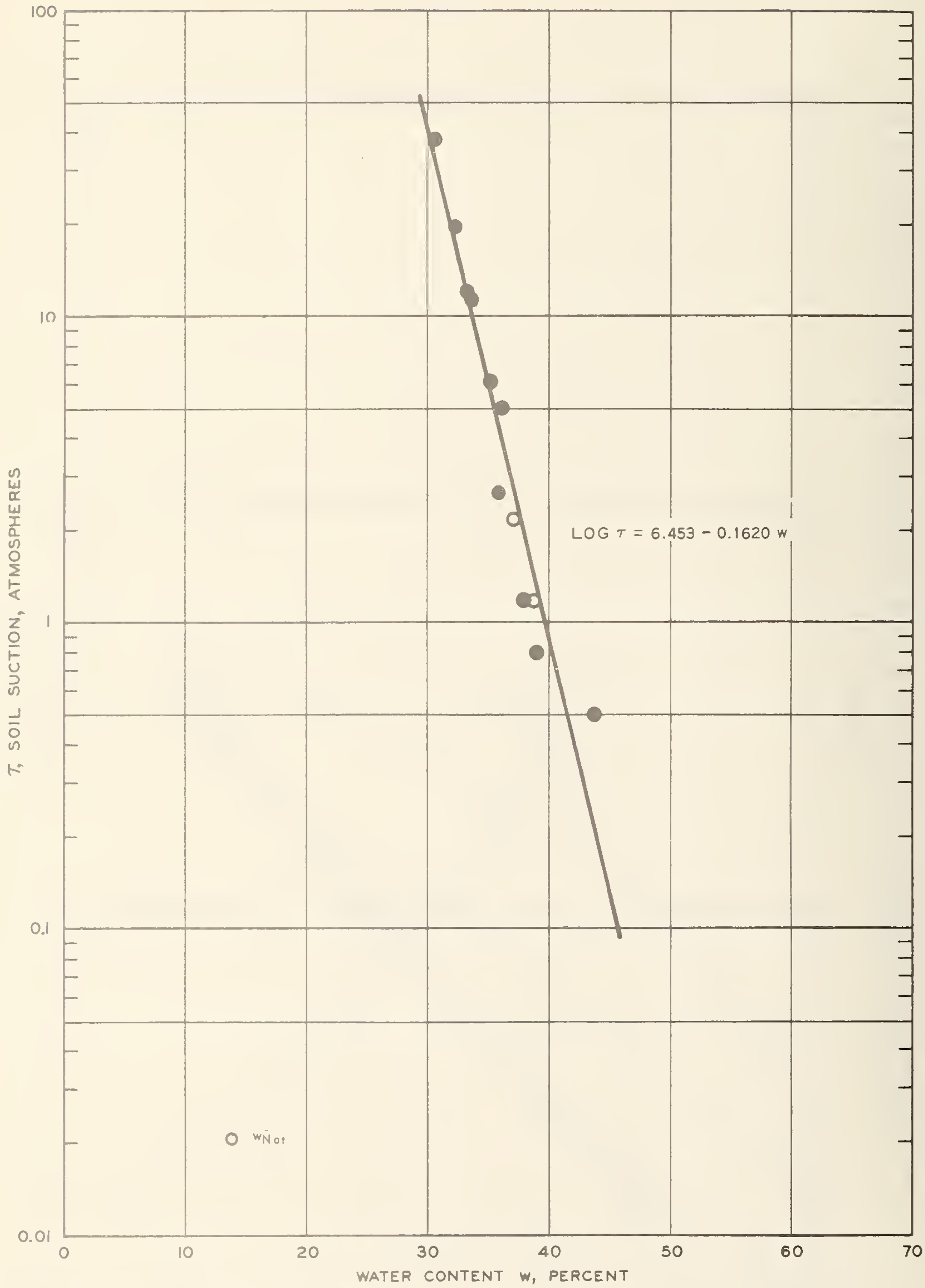
OVERBURDEN SWELL TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

SITE Limon, Colo. (No. 2, I-70) BORING U-1 SAMPLE No. 1 DEPTH 3.4-5.0 ft



CONSTANT VOLUME SWELL PRESSURE TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

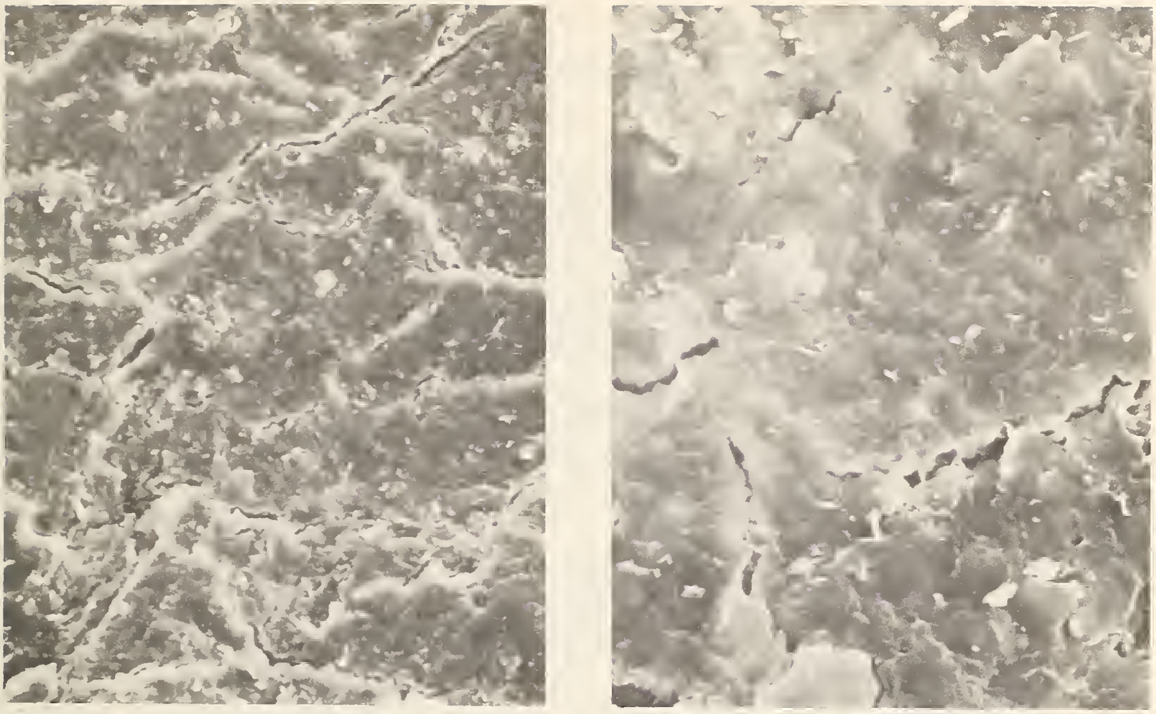
SITE Limon, Colo. (No. 2, I-70) BORING U-1 SAMPLE No. 1 DEPTH 3.4-5.0 ft



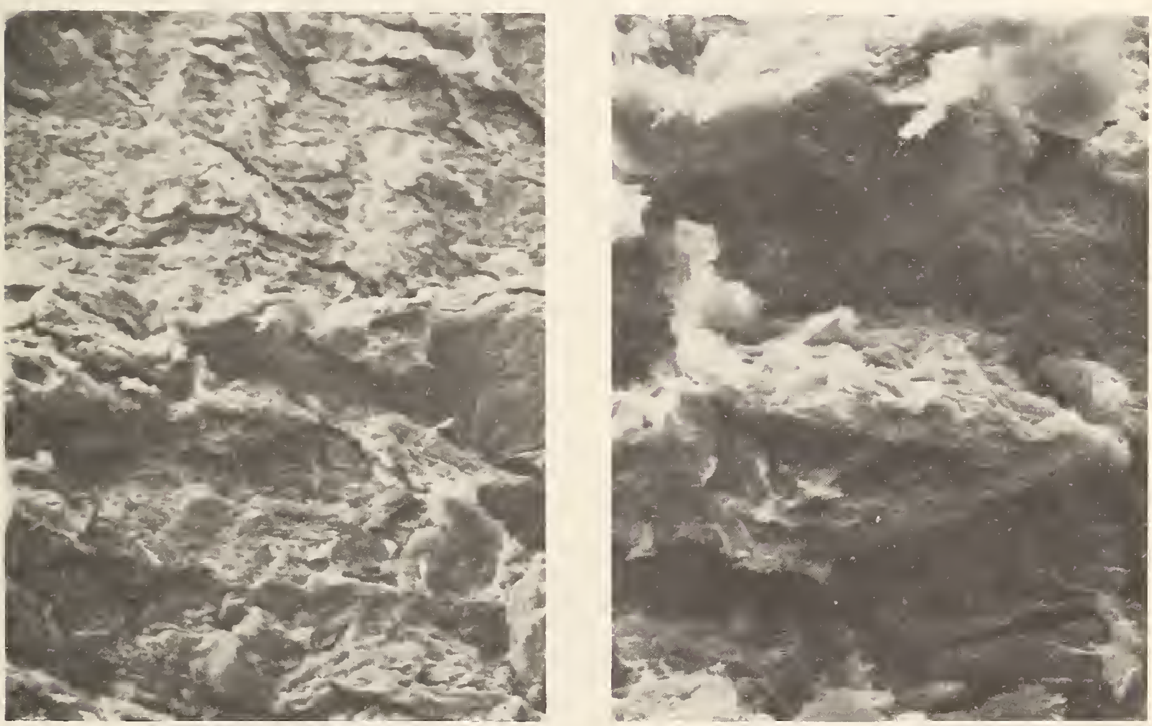
SOIL SUCTION VERSUS WATER CONTENT

SITE Limon, Colo. (No. 2, I-70) BORING U-1

SAMPLE No. 1 DEPTH 3.4-5.0 ft



a. Normal to Y, ×650 and ×2300



10 μm

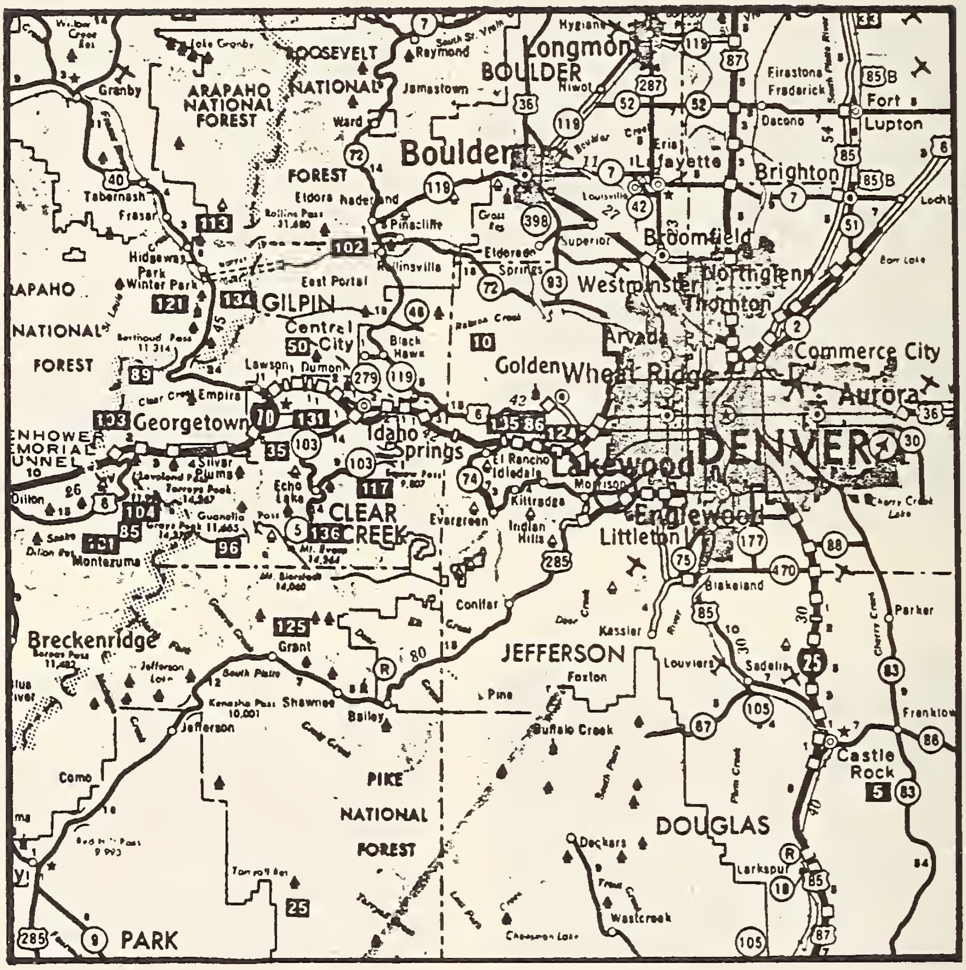
10 μm

b. Normal to X, ×650 and ×2300

SITE Limon, Colo. (No. 2, I-70) BORING U-1

SAMPLE No. 1 DEPTH 3.4-5.0 ft

SAMPLING SITE NO. 16, DENVER, COLO.



Site Location Information

183. Sampling site No. 16 is located in central Colorado southwest of Denver near Morrison, Colo. The site is located on SH 48 1.8 miles east of the junction of SH 8 and SH 74 in Morrison. Samples were taken in north right-of-way near station 132+00 prior to completion of construction. Field monitoring section is between stations 72+00 and 77+00.

Site Description

184. Sampling site and field-monitoring section are located in a cut section (depth ≈ 15 to 20 ft) in hilly terrain. Drainage is in an

easterly direction on a moderate slope. Surrounding area has partial grass cover and no trees.

Site Geology

185. Sampling site is located in the Colorado Piedmont Section of the Great Plains Physiographic Province near the boundary between this province and the Southern Rocky Mountains Physiographic Provinces. Topography consists of elevated plains with low to moderate relief. Samples were taken in the Denver Formation of the Paleocene to Eocene Series, Tertiary System. The Denver Formation consists of interbedded and gradational facies of sandstone agglomerate, shale, volcanic agglomerates, and volcanic flows. The thickness of the Denver Formation may vary to a maximum of 8000 ft. It overlies the sandstone, shale, tuff, and coal of the Cretaceous Laramie Formation.

Sample Description

186. The Denver Formation as sampled near Denver, Colo., is a hard, indurated, highly weathered, noncalcareous, yellowish gray (5 Y 7/2) mudrock. Silt size grains are common and bedding is not evident. Mica is a common accessory mineral. The yellow color of the material is partially due to numerous iron oxide stains. Locally some areas are stained and partially cemented by black iron or manganese cement. The SEM photographs indicate an agglomerated fabric not well developed.

Description of Climate

187. Most of Colorado has a cool and invigorating climate which could be termed a highland or mountain climate of a continental location. During summer there are hot days in the plains, but these are often relieved by afternoon thundershowers. Mountain regions are nearly always cool. Humidity is generally quite low; this favors rapid evaporation and a relatively comfortable feeling even on hot days. The thin atmosphere allows greater penetration of solar radiation and results in pleasant daytime conditions even during the winter. This is why skiers at high elevations are often pictured in very light clothing, although surrounded by heavy snow.

188. The climates of local areas are profoundly affected by differences in elevation, and to a lesser degree, by the orientation of

mountain ranges and valleys with respect to general air movements. Wide variations occur within short distances. The difference (35°F) in annual mean temperature between Pikes Peak and Las Animas, 90 miles to the southeast, is about the same as that between southern Florida and Iceland. The average annual snowfall at Cumbres in the southern mountains is nearly 300 in.; less than 30 miles away at Manassa in the San Luis Valley, snowfall is less than 25 in. While temperature decreases, and precipitation generally increases with altitude, these patterns are modified by the orientation of mountain slopes with respect to the prevailing winds and by the effect of topographical features in creating local air movements.

189. As a result of the State's distance from major sources of moisture (the Pacific Ocean and the Gulf of Mexico), precipitation is generally light in the lower elevations. Prevailing air currents reach Colorado from westerly directions. Eastward-moving storms originating in the Pacific Ocean lose much of their moisture in passage over mountain ranges to the west; a large part of the remaining moisture falls as rain or snow on the mountaintops and westward-facing slopes. Eastern slope areas receive relatively small amounts of precipitation from these storms.

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191. An important feature of the precipitation in the plains is the large proportion of the annual total which falls in the growing

season--70 to 80 percent during the period from April through September. Summer precipitation in the plains is largely from thunderstorm activity and is sometimes extremely heavy. Strong winds occur frequently in winter and spring. These winds tend to dry out soils, which are not well supplied with moisture because of the low annual precipitation. During periods of drought such winds give rise to the dust storms which are especially characteristic of the southeastern plains.

192. At the western edge of the plains and near the foothills of the mountains, there are a number of significant changes in climate as compared to the plains proper. Average wind movement is less, but areas very near the mountains are subject to periodic, severe turbulent winds from the effects of mountain waves generated by the flow of high westerly winds over the mountain barrier. Temperature changes from day to day are not as great; summer temperatures are lower, and winter temperatures are higher. Precipitation, which decreases gradually from the eastern border to a minimum near the mountains, increases rapidly with the increasing elevation of the foothills and proximity to the higher ranges. The decrease in temperature from the eastern boundary westward to the foothills is less than might be expected with increasing altitude. This results from mountain and valley winds and greater frequency of the Chinook. Below the Royal Gorge, the mountain and valley winds are strong enough to modify the climate of a considerable area. Descending air currents frequently prevent the stratification of air necessary for the occurrence of excessive cold. As a consequence, the winter climate is milder than elsewhere in the State.

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the mountains is a cool and refreshing season. At typical mountain stations the average July temperature is in the neighborhood of 60°F. The highest temperatures are usually in the seventies and eighties, but may reach 90 to 95°F. Above 7000 ft, the nights are quite cool throughout the summer, while bright sunshine makes the days confortably warm.

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195. Precipitation west of the Continental Divide is more evenly distributed throughout the year than in the eastern plains. For most of western Colorado, the greatest monthly precipitation occurs in the winter months, while June is the driest month. In contrast, June is one of the wetter months in most of the eastern part of the State.

Climatic Data Summary

Reporting Station: Lakewood (05-4762-04)

Mean Monthly Temperature and Normal
Monthly Precipitation for Period 1941-70:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature, °F	31.9	34.9	38.5	48.7	57.7	66.7	73.1	71.4	62.9	52.7	40.7	34.5	51.1
Precipitation, in.	0.64	0.62	1.16	1.97	2.53	1.84	1.61	1.22	1.10	1.12	0.75	0.39	14.95

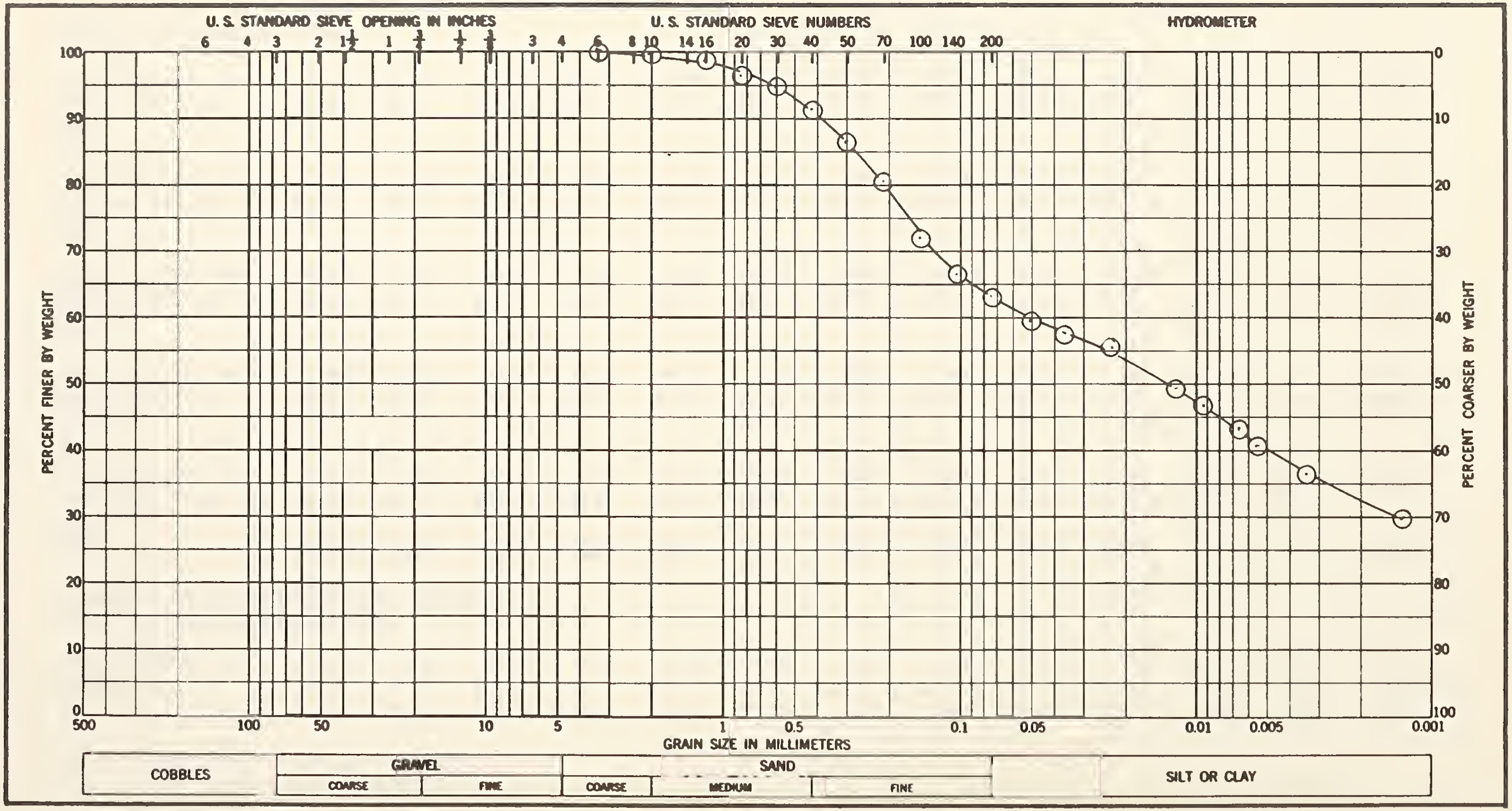
Average Monthly Temperature and
Total Monthly Precipitation for 1971-75:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1971													
Temperature, °F	34.0	31.5	39.1	44.4	53.7	68.6	70.3	72.3	57.9	50.3	39.6	31.7	49.5
Precipitation, in.	0.35	1.07	0.51	3.36	1.75	0.79	0.77	0.67	3.25	0.69	0.37	0.26	13.84
1972													
Temperature, °F	30.7	36.8	45.7	48.1	54.6	67.6	69.0	69.5	61.0	50.4	32.3	26.6	49.4
Precipitation, in.	0.50	0.52	0.68	2.14	0.81	1.04	1.50	2.62	1.34	1.28	2.82	0.70	15.95
1973													
Temperature, °F	27.4	33.1	37.9	39.5	52.5	66.6	68.4	72.2	58.4	53.3	38.3	34.1	48.5
Precipitation, in.	1.14	0.05	2.67	3.64	5.88	2.27	3.82	0.92	2.01	0.65	0.95	1.64	25.64
1974													
Temperature, °F	26.4	33.4	42.1	46.7	60.0	67.1	73.2	67.5	57.7	52.3	39.4	31.2	49.8
Precipitation, in.	1.35	0.76	0.94	1.31	0.20	2.32	1.07	0.23	1.33	2.00	1.16	0.62	13.29
1975													
Temperature, °F	29.8	28.9	36.0	42.0	52.6	63.2	71.9	70.1	58.0	53.5	36.5	36.7	48.3
Precipitation, in.	0.35	0.58	0.76	1.55	3.18	1.93	4.29	2.49	0.33	0.41	1.88	0.32	18.07

Thornthwaite Moisture Index:

1970	1971	1972	1973	1974	1975
2.91	-4.29	-14.05	6.20	-9.06	-3.52

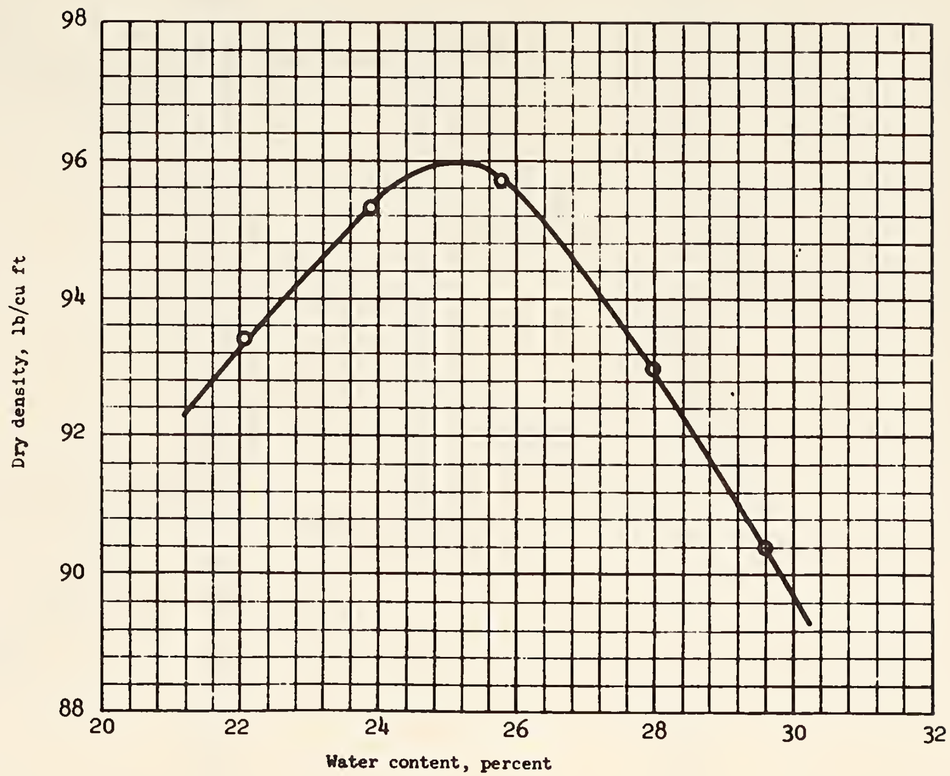
Avg = -3.64



GRADATION CURVE

SITE Denver, Colo. BORING U-3

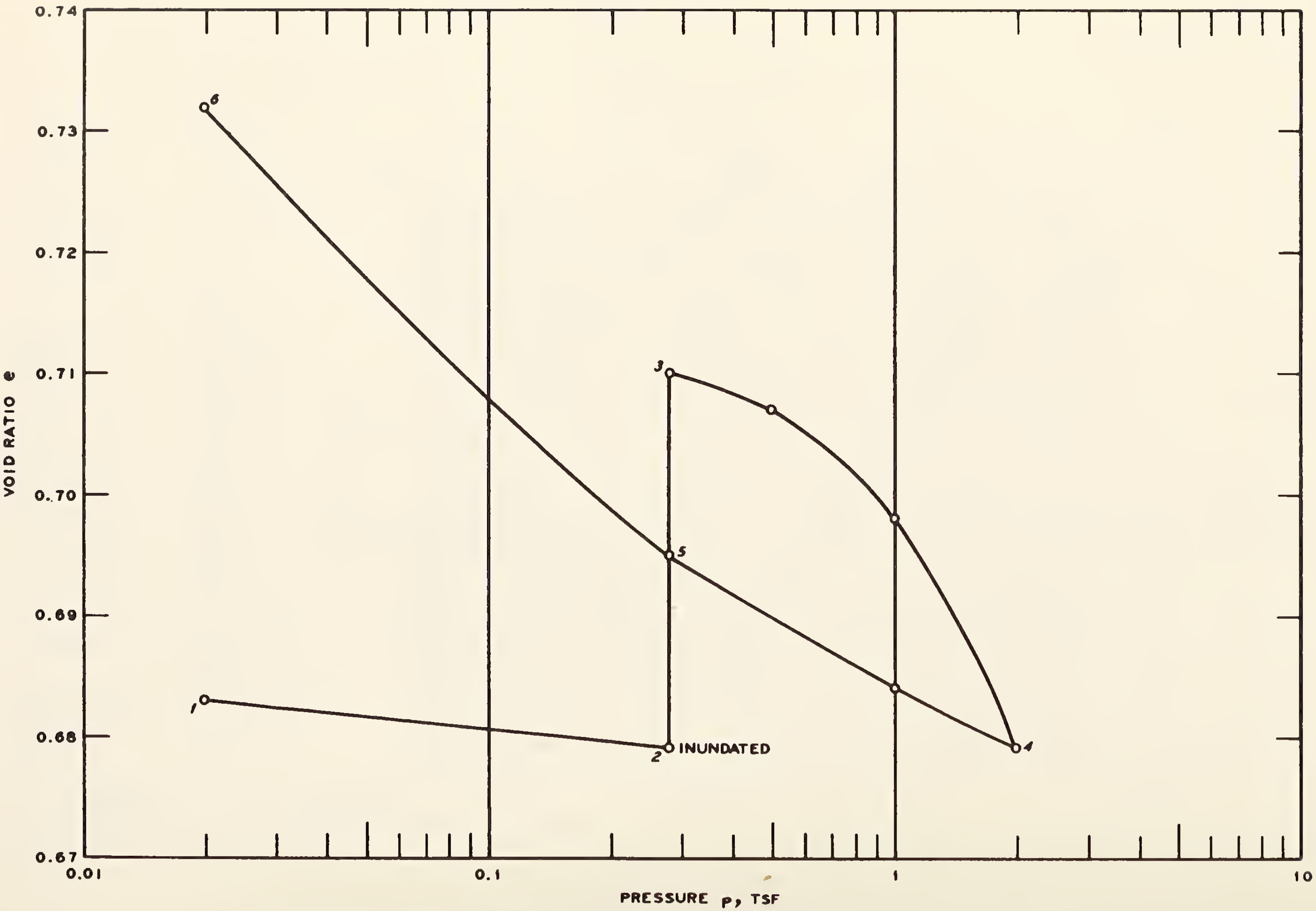
SAMPLE No. 4 DEPTH 5.7-7.8 ft



COMPACTION CURVE

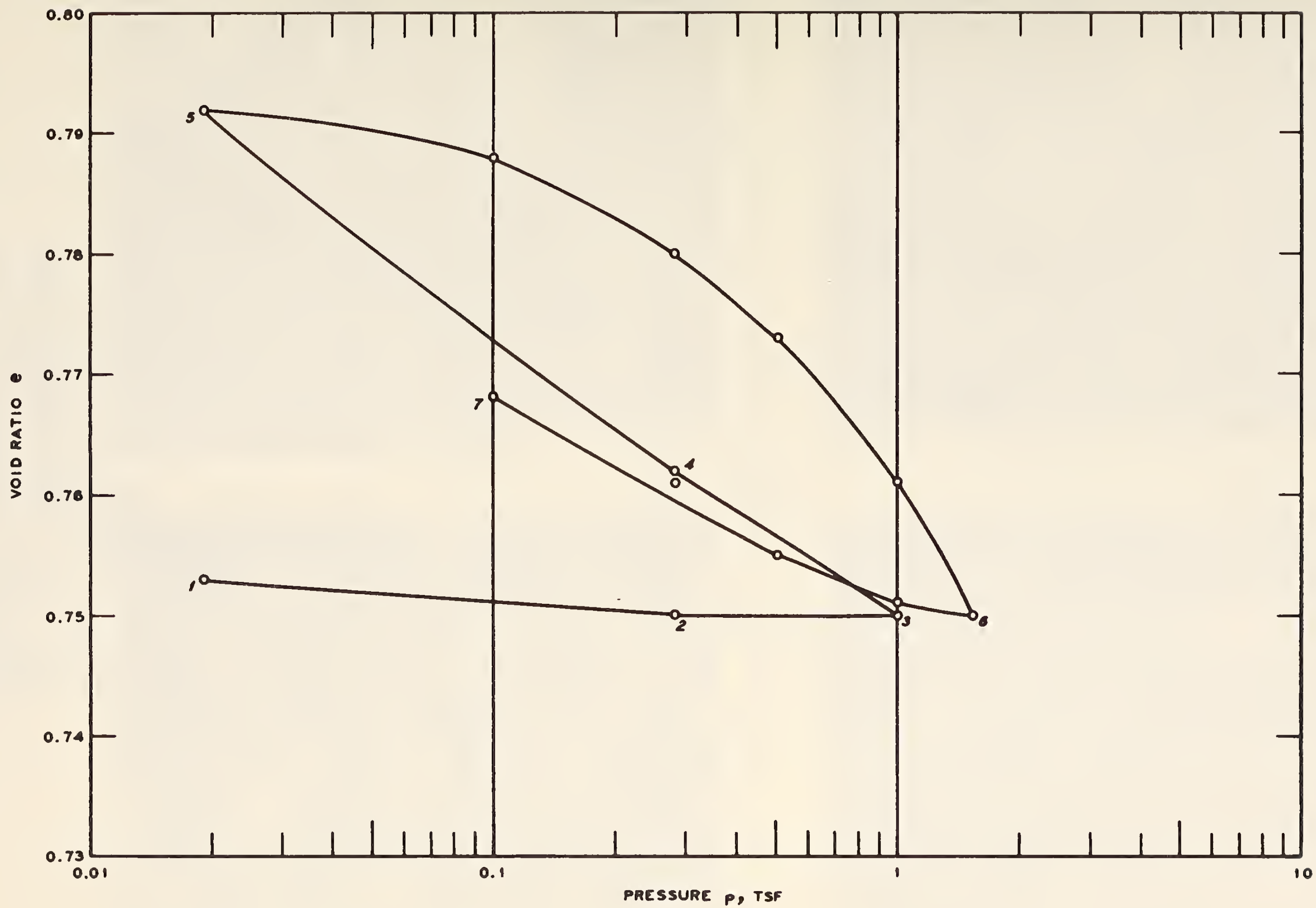
SITE Denver, Colo.

SAMPLE Disturbed



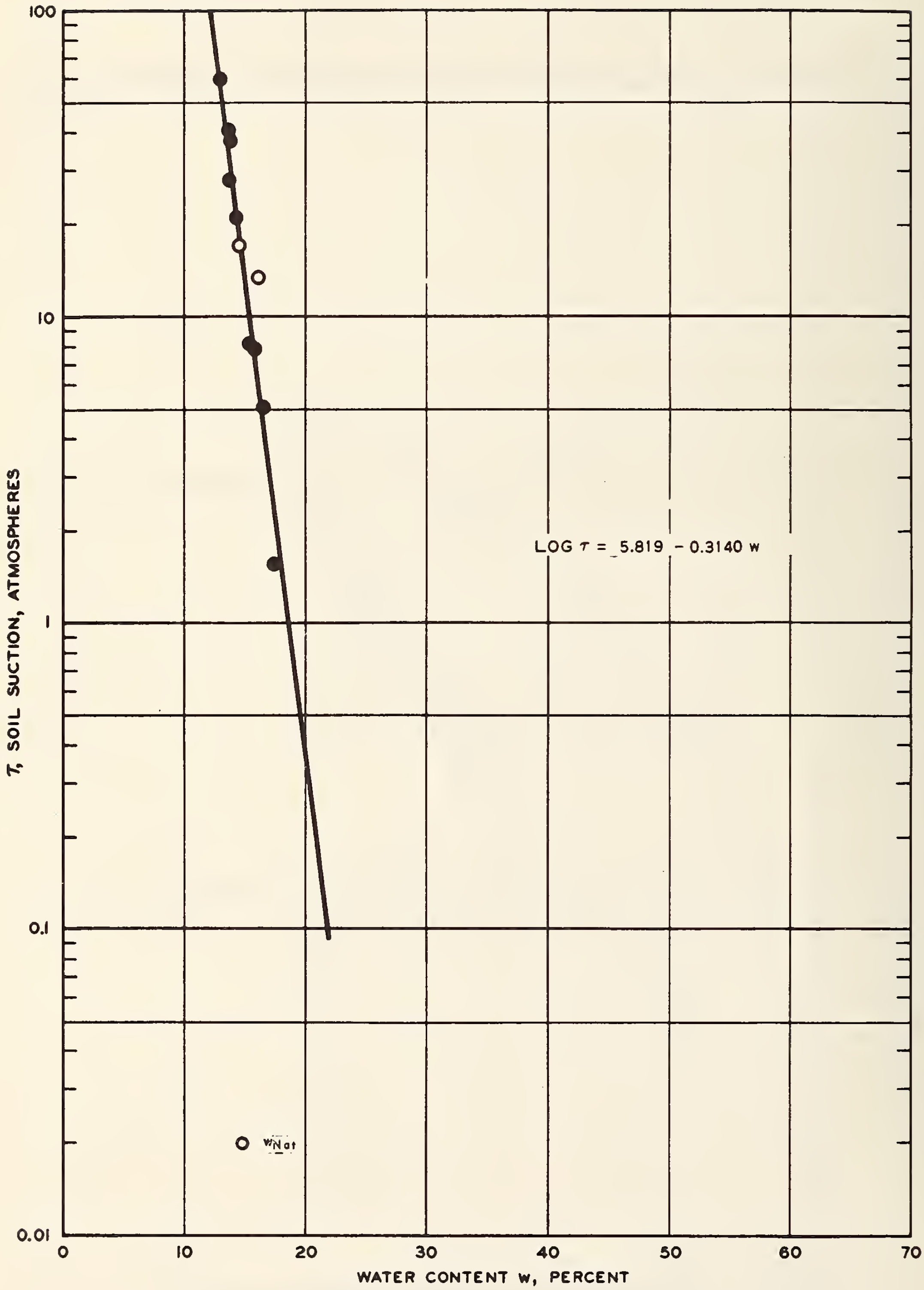
OVERBURDEN SWELL TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

SITE Denver, Colo. BORING U-3 SAMPLE No. 4 DEPTH 5.7-7.8 ft



CONSTANT VOLUME SWELL PRESSURE TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

SITE Denver, Colo. BORING U-3 SAMPLE No. 4 DEPTH 5.7-7.8 ft

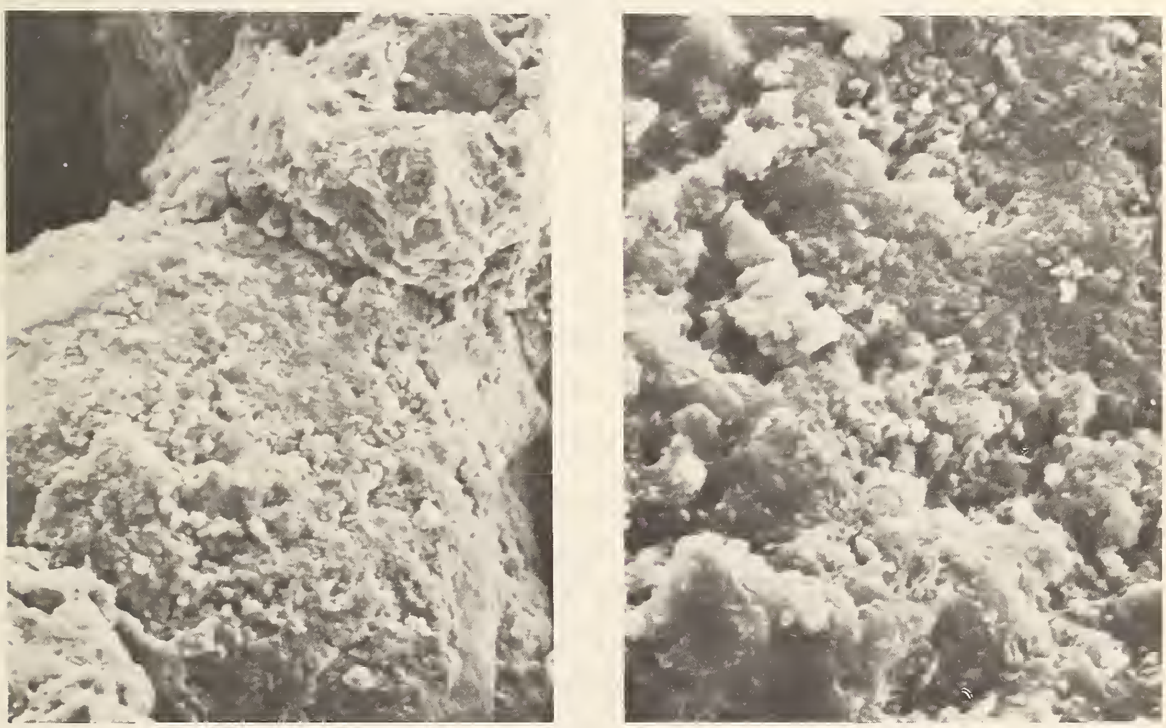


SOIL SUCTION VERSUS WATER CONTENT

SITE Denver, Colo. BORING U-3

SAMPLE No. 4 DEPTH 5.7-7.8 ft

a. Normal to Y, ×650 and ×2300



10 μm

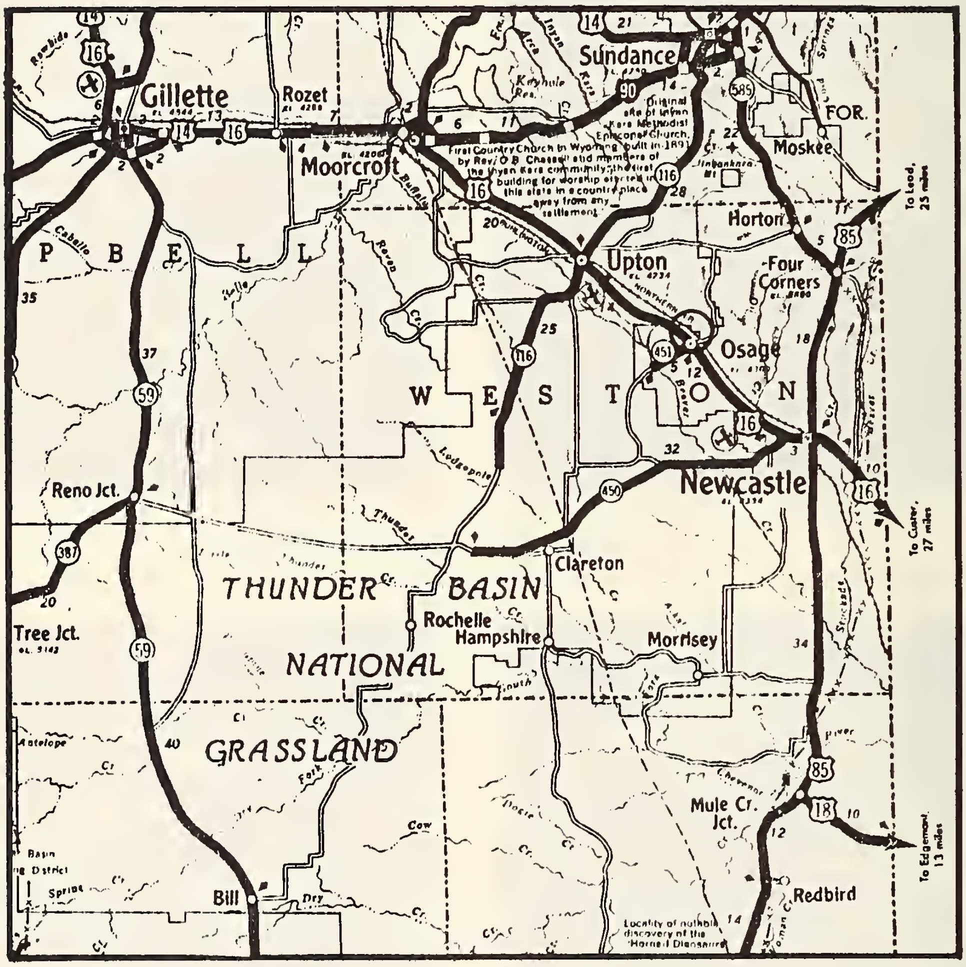
b. Normal to X, ×650 and ×2300

10 μm

SITE Denver, Colo. BORING U-3

SAMPLE No. 4 DEPTH 5.7-7.8 ft

SAMPLING SITE NO. 17, NEWCASTLE, WYO.
(No. 1, SH 16)



Site Location Information

196. Sampling site No. 17 is located in northeastern Wyoming approximately 16 miles northwest of Newcastle, Wyo. The site is located approximately 0.5 mile northwest of the U. S. 16 and SH 451 junction (Osage, Wyo.) on U. S. 16. Samples were taken in the east right-of-way, approximately 35 ft from the pavement centerline, of the Oil City Road approximately 320 ft south of its junction with U. S. 16; near milepost 33 on U. S. 16.

Site Description

197. Sampling site is located at grade in open, gently rolling terrain. Drainage is in a northeasterly direction on a gentle slope. Surrounding area has a full grass cover and no trees.

Site Geology

198. Sampling site is located near the boundaries of the Black Hills and the Unglaciated Missouri Plateau Sections of the Great Plains Physiographic Provinces. Samples were taken from the Mowry-Belle-Fourche Formation of the Colorado Group, Cretaceous System. The Mowry-Belle-Fourche is approximately 700 ft thick in the site area. The material is predominantly shale with bentonite and sandstone layers. The Mowry-Belle-Fourche is overlain by the Greenhorn Formation and underlain by the Newcastle Formation.

Sample Description

199. The Mowry Formation as sampled is a hard, indurated, weathered, noncalcareous, medium dark gray (N4) clay shale. The material exhibits well-developed stratifications with no visible voids. Weathered surfaces exhibit microscopic clusters of crystals, possibly gypsum. The SEM photographs indicate a moderately developed face-to-face particle orientation.

Description of Climate

200. Like the other States in the western part of the country, precipitation varies considerably from one location to another. The period of maximum precipitation occurs in the spring and early summer for most of the State. It is greater over the mountain ranges and usually at the higher elevations, although elevation alone is not the only influence. For example, over most of the southwest portion, where the elevation ranges from about 6500 to 8500 ft above sea level, annual precipitation values vary from 7 to 10 in., while at much lower elevations over the northeast portion and along the east border, where elevations are mostly in the range from 4000 to 5500 ft, annual averages are generally from 12 to 16 in. The relatively dry southwest portion is a high plateau nearly surrounded by mountain ranges.

201. The Big Horn Basin provides a striking example of the effect

of mountain ranges in blocking the flow of moisture laden air from the east as well as from the west. The lower portion of the Basin has an annual precipitation in the range of 5 to 8 in., and it is the driest part of the State. The station showing the least amount is Denver at 4105 ft with an annual mean of only 5.31 in. In the southern part of the Basin, Worland at 4061 ft has an annual mean of 8.15 in. as compared with Termopolis at 4313 ft and 11.15 in. There is another good example in the southeastern part of the State where Laramie at 7236 ft has an annual mean of 11.16 in., while 30 miles to the west, Centennial at 8074 ft received 16.47 in.

202. Snow falls frequently from November through May. Generally, snowfall at lower elevations is light to moderate. About five times a year on the average, stations at the lower elevations will have snowfall exceeding 5 in. Falls of 10 to 15 in. or more for any one storm are occasional but infrequent outside of the mountains. Of course, wind will frequently accompany or follow a snowstorm and pile the snow into drifts several feet deep. Frequently the snow drifts so much that it is difficult to obtain an accurate measurement of snowfall.

203. The total annual amount of snow varies considerably over the State as does the rainfall. At the lower elevations of the east portion, the range is mostly from 60 to 70 in. annually. Over the drier southwest portion, amounts vary from 45 to 55 in. at most places. Snow is very light in the Big Horn Basin with annual averages from 15 to 20 in. over the lower portion to 30 to 40 in. on the sides of the Basin where elevations range from 5000 to 6000 ft. Of course the mountains receive a great deal more and over the higher ranges annual amounts are well over 200 in. At Beckler River Ranger Station in the southwest corner of Yellowstone Park, the snowfall averaged 262 in. for a 20-year period.

204. The weather map pattern most favorable for precipitation is one showing a storm center over or a little to the south of the State. This would normally provide a condition where relatively cool air at the surface is overrun by warmer air aloft having farily high humidity. The numerous low pressure systems that first show up on the continent in the Alberta area of Canada and move to the southeast over the northern

plains frequently cause very strong and gusty winds over Wyoming but not much precipitation, especially at the lower elevations. Studies of wind flow patterns indicate that Wyoming is covered most of the time by air from the Pacific. A smaller percentage of the time the State is covered by cold air masses that move down from Canada, but these usually modify rapidly after reaching this area. It is seldom that air reaches Wyoming from the Gulf of Mexico, the source credited with most of the precipitation over the Mississippi Valley.

205. Because of the elevation, Wyoming has a relatively cool climate. Above the 6000-ft level the temperature rarely exceeds 100°F. The warmest parts of the State are the lower portion of the Big Horn Basin, the lower elevations of the central and northeast portions, and along the east border. The highest recorded temperature was 114°F on July 12, 1900, at Basin in the Big Horn Basin. The average high temperature at Basin in July is 92°F. For most of the State, mean high temperatures in July range between 85 and 90°F. With increasing elevation, average values drop rapidly. A few places in the mountains at about the 9000-ft level show an average high in July close to 70°F. Summer nights are almost invariably cool, even though daytime readings may be quite high at times. For most places outside of the mountains, the mean low temperature in July is in the range from 50 to 60°F. Of course, the mountains and high valleys are much cooler with average lows in the middle of the summer in the 30's and low 40's with occasional drops below freezing.

206. In the wintertime it is characteristic to have rapid and frequent changes between mild and cold spells. Usually there are less than 10 cold waves during a winter, and frequently less than half that number for most of the State. The majority of cold waves move southward on the east side of the Divide, with only an occasional cold wave for the west side. Sometimes only the northeast portion will be affected by the cold air as it slides on to the east over the plains. Many of the cold waves are not accompanied by enough snow to cause severe conditions. In January--the coldest month generally--mean minimum temperatures range mostly from 5 to 15°F. In the western valleys mean values go down to

about 5°F below zero. The record low for the State is -63°F observed February 9, 1963, at Moran in Teton County. During warm spells in the winter, nighttime temperatures frequently remain above freezing. Chinooks are common along the eastern slopes.

207. For most of the State, sunshine ranges from approximately 60 percent of the possible amount during the winter to about 75 percent during the summer. Mountain areas receive less, and in the wintertime the estimated amount over the northwestern mountains is about 45 percent. Although the average amount of sunshine is less in winter, the low point on the annual variations is not during the coldest month (January or February). One low period of sunshine comes in November or December, and another in April or May. These periods of low sunshine correspond fairly close to the periods of greatest temperature changes, i.e., in the late fall when average temperatures are dropping rapidly and in the spring when the average is climbing rapidly. To be sure, sunshine will not be much higher during the coldest months, but cold air masses are apt to be more stable at that time, and frontal activity is followed by a slightly longer period of sunshine. In the summertime when sunshine is greatest--not only in time but also intensity--it is characteristic for the forenoons to be mostly clear. Cumulus clouds develop nearly every day and frequently blot out the sun for a portion of the afternoons. Because of the altitude--providing less atmosphere for the sun's rays to penetrate--and because of the very small amount of fog, haze, and smoke, the intensity of sunshine is unusually high.

208. Wind is an important factor of the Wyoming climate. This is largely due to the high elevation and enormous stretches of rolling plains. Over the higher south portion, average annual wind speeds range from 12 to 14 mph. Much of the north portion, being considerably lower in elevation has a lower average speed. There are some favorable locations which are protected from the wind by mountain ranges. Lander is one such place and has an annual average of only 7.0 mph at the airport station. The records for the city of Lander show even lighter winds. The lower portion of the Big Horn Basin at such places as Worland and Basin very light winds. However, most of Wyoming is quite windy, and

during the colder months from November through March there are frequent periods when the wind reaches 30 to 40 mph with occasional gusts much higher. Prevailing directions in the different localities vary from west-southwest through west to northwest. In many localities winds are so strong and constant from those directions that trees show a definite lean toward the east or southeast.

209. The average relative humidity is quite low and, while this has a distinct advantage in providing delightful summer weather, it is related to the rather low amount of moisture. During the warmer part of the summer days, the average drops to about 25 to 30 percent, and on a few occasions it will be as low as 5 to 10 percent. Late at night when the temperature is lowest the humidity will generally be up to 65 to 75 percent. This results in an average diurnal variation of about 40 to 45 percent during the summer, but in the winter the variation is much less. Low relative humidity, high percentage of sunshine, and rather high average winds add their influence in causing a large amount of evaporation. Because of frequent spells of freezing weather before May 1 and after September 30, it is difficult to obtain consistent records of evaporation for more than the 5-month period from May through September. For this period, the average amount of evaporation is approximately 41 in., as determined from evaporation pans at a few selected locations. The overall range is from a little more than 31 in. at Archer and Sheridan Field Station to near 47 in. at Farson and Boysen Dam.

Climatic Data Summary

Reporting Station: Newcastle (48-6660-07)

Mean Monthly Temperature and Normal
Monthly Precipitation for Period 1941-70:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature, °F	22.9	26.9	32.1	44.7	55.1	64.1	73.0	71.6	59.9	49.2	34.6	26.3	46.7
Precipitation, in.	0.39	0.42	0.68	1.50	2.48	2.94	1.77	1.38	1.03	0.61	0.45	0.45	14.10

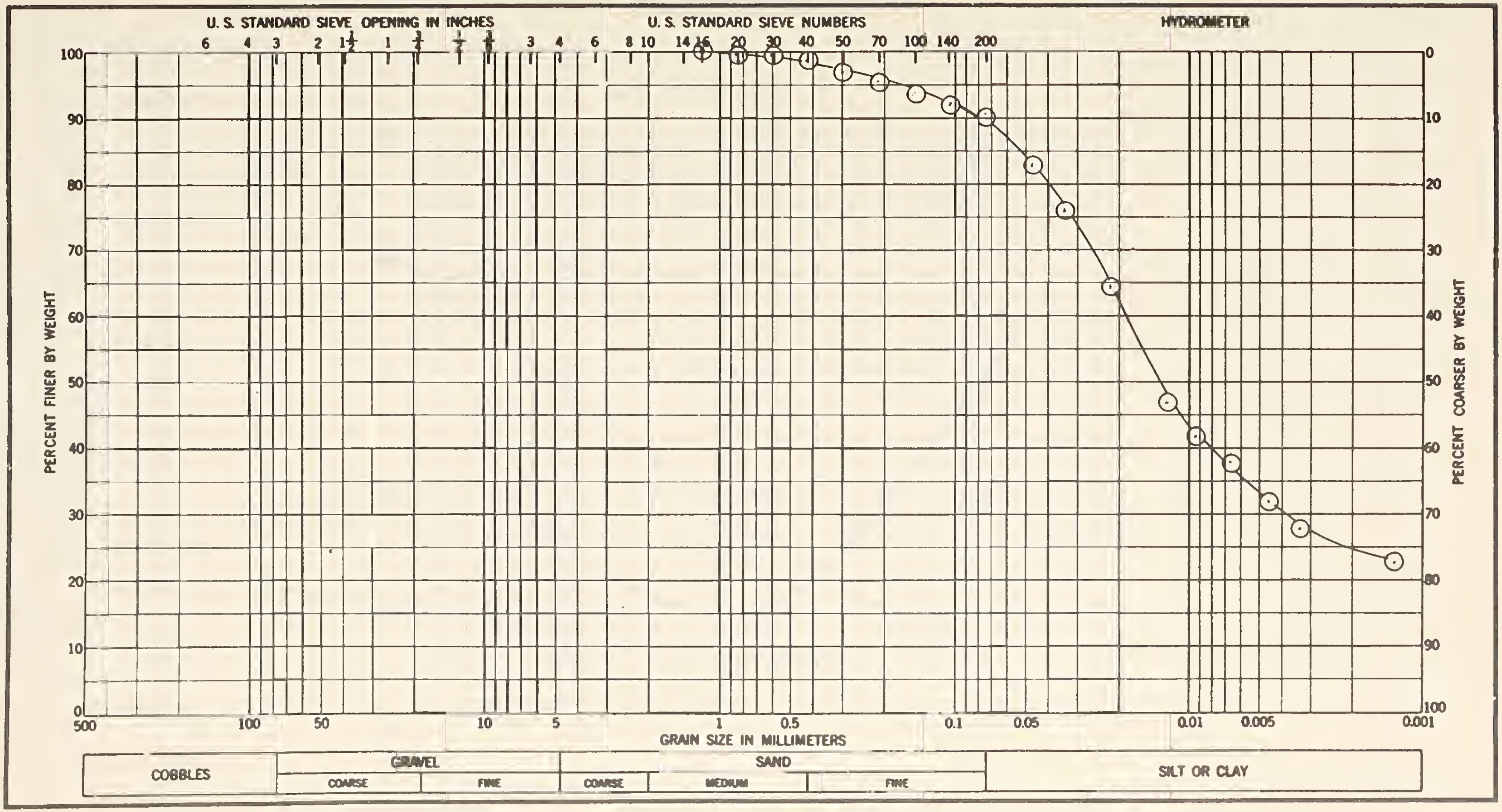
Average Monthly Temperature and
Total Monthly Precipitation for 1971-75:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1971													
Temperature, °F	23.3	23.1	28.7	--*	--*	67.0	69.4	74.6	57.6	--*	--*	--*	--
Precipitation, in.	0.56	0.66	0.13	3.20	--*	1.55	0.61	0.41	1.23	2.33	--*	0.13	--
1972													
Temperature, °F	14.8	24.1	--*	43.8	--*	--*	--*	69.6	57.8	45.8	30.7	17.3	--
Precipitation, in.	0.95	0.50	--*	0.91	--*	--*	2.94	3.98	0.82	0.54	0.34	0.51	--
1973													
Temperature, °F	21.4	28.1	36.8	40.6	53.4	65.4	71.6	72.1	57.0	49.4	32.1	25.9	46.2
Precipitation, in.	0.07	0.33	1.01	2.34	0.47	2.50	2.33	1.18	3.21	0.69	0.75	1.04	15.92
1974													
Temperature, °F	19.1	30.3	37.1	47.9	55.2	68.8	76.1	67.2	56.5	50.4	34.4	24.8	47.3
Precipitation, in.	0.43	0.22	0.07	0.86	0.70	0.62	2.14	2.87	0.96	1.69	0.31	0.43	11.30
1975													
Temperature, °F	21.7	20.7	30.2	40.3	54.4	62.0	75.2	70.5	57.4	48.3	31.2	28.3	45.0
Precipitation, in.	0.65	0.40	1.38	2.87	2.93	3.70	0.75	0.15	0.05	1.01	0.43	0.59	14.91

Thornthwaite Moisture Index:

1970	1971	1972	1973	1974	1975	
-18.29	-7.26	-5.95	-5.96	-22.62	-17.59	Avg = -12.95

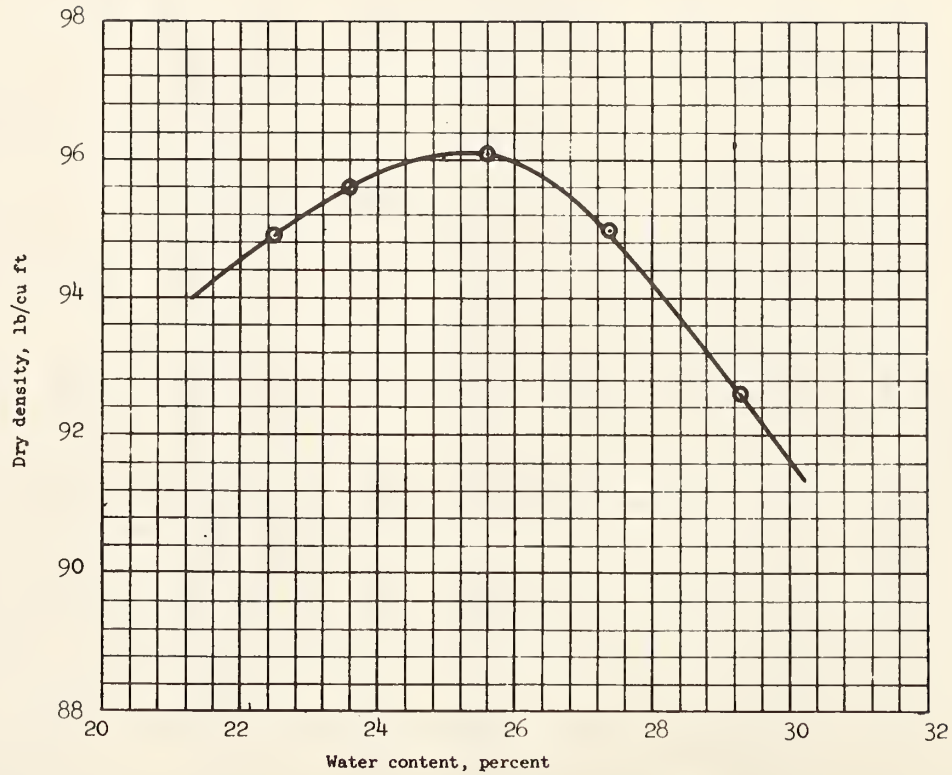
* Record missing.



GRADATION CURVE

SITE Newcastle, Wyo. (No. 1, SH 16) BORING U-2

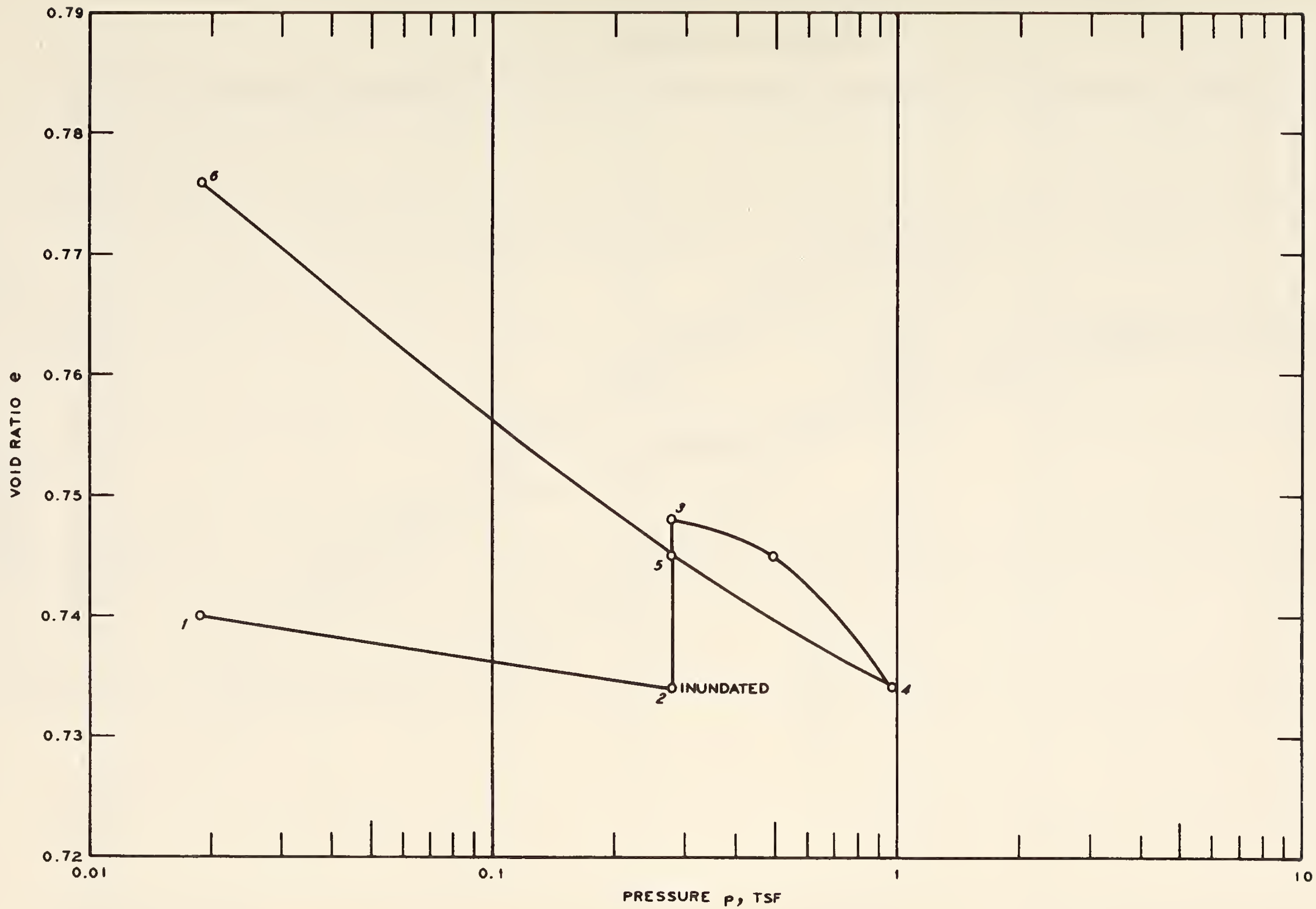
SAMPLE No. 1 DEPTH 3.0-5.2 ft



COMPACTION CURVE

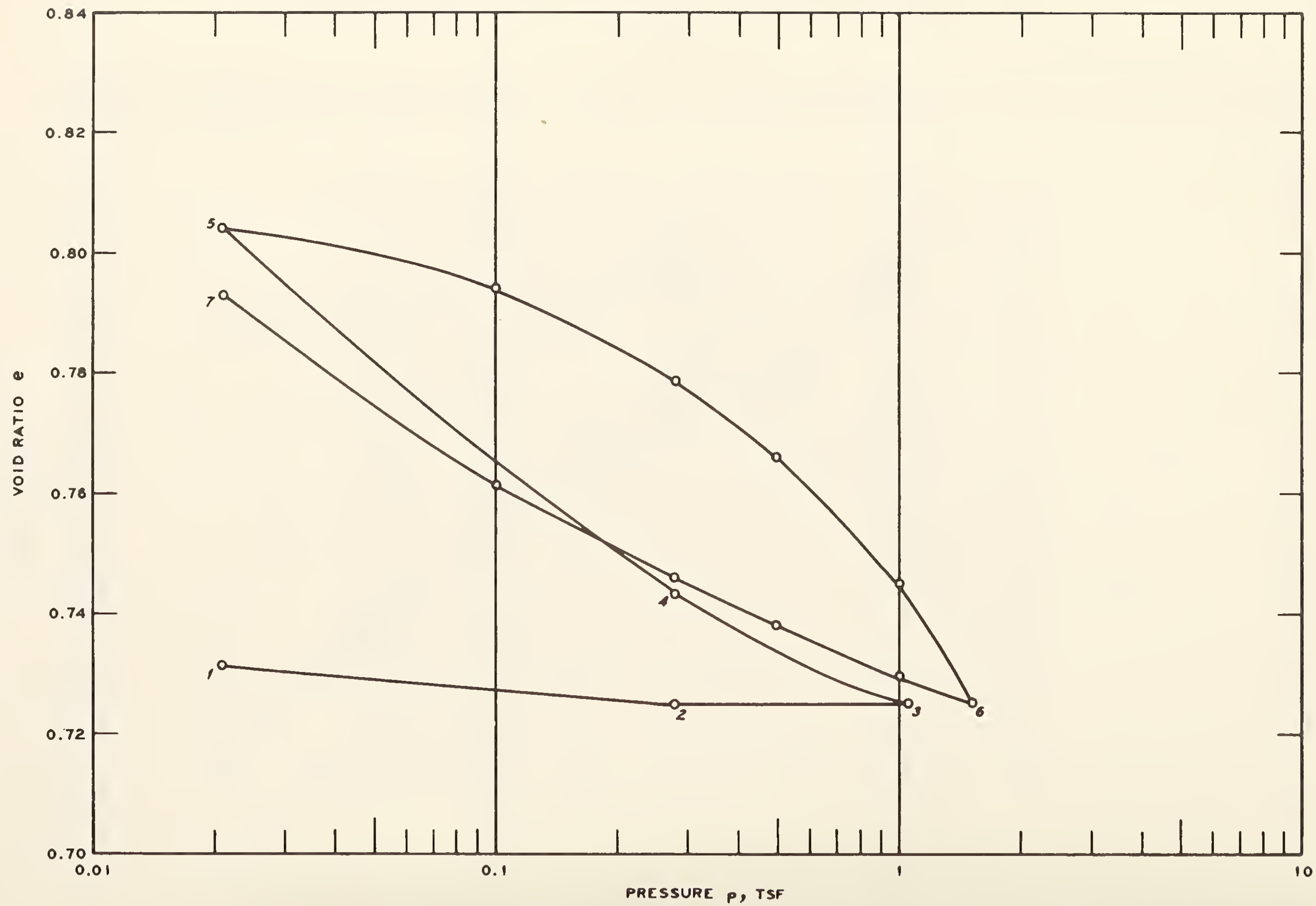
SITE Newcastle, Wyo. (No. 1, SH 16)

SAMPLE Disturbed



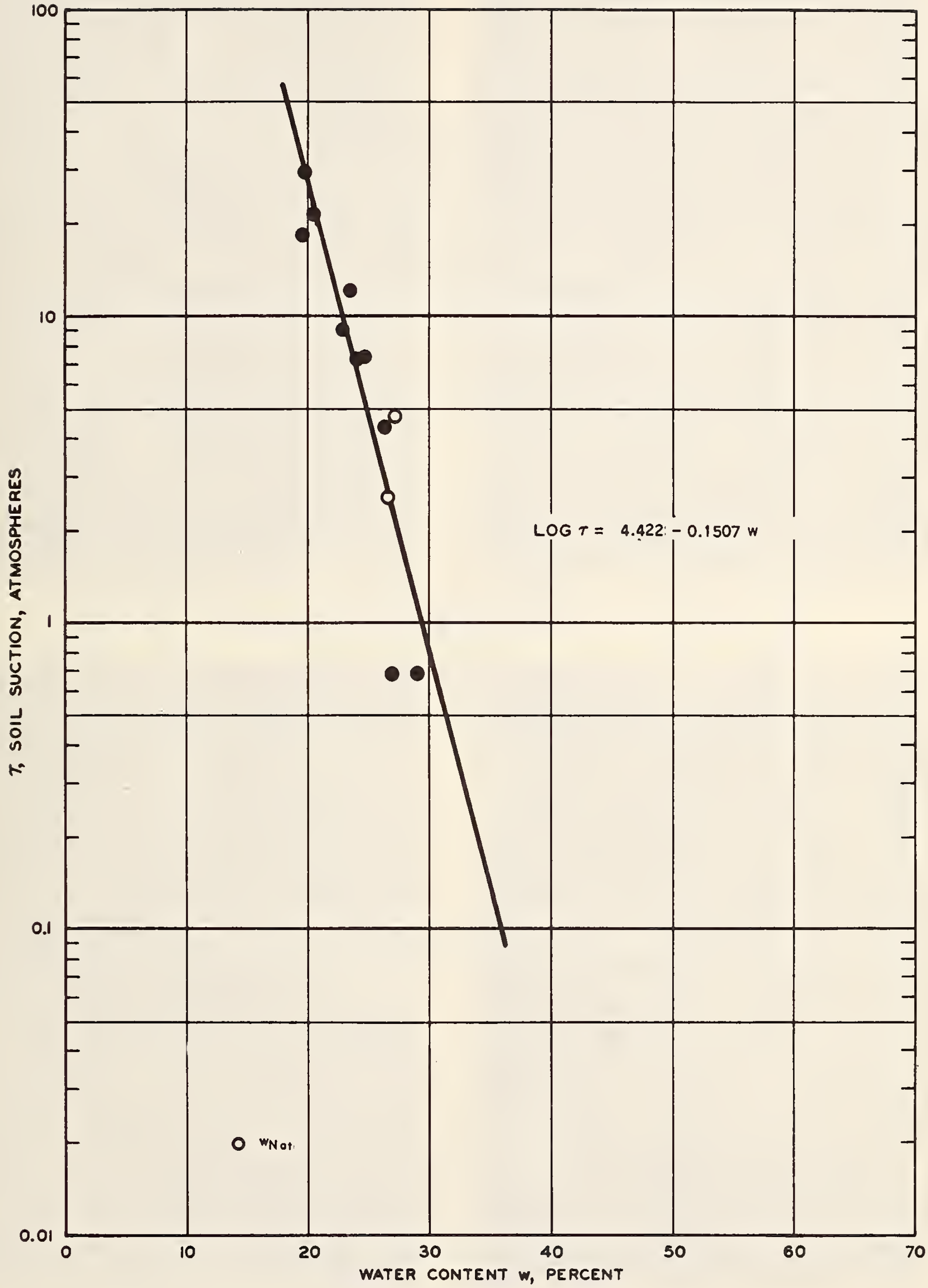
OVERBURDEN SWELL TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

SITE Newcastle, Wyo. (No. 1, SH 16) BORING U-2 SAMPLE No. 1 DEPTH 3.0-5.2 ft



CONSTANT VOLUME SWELL PRESSURE TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

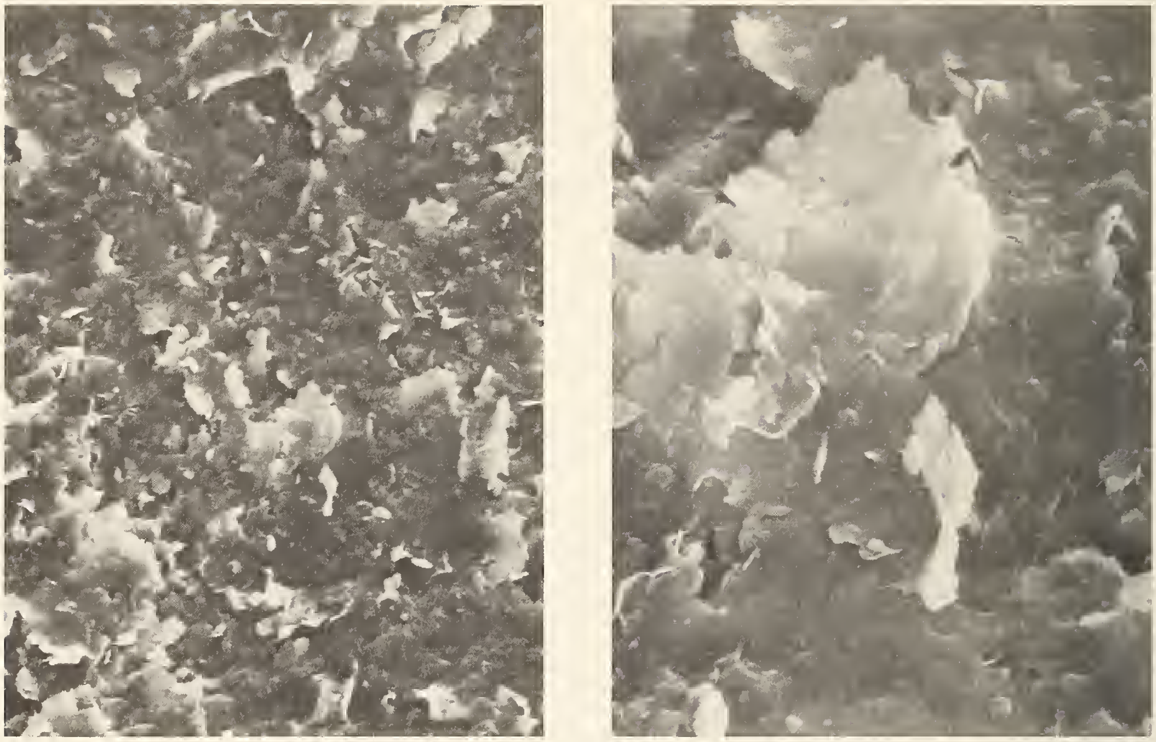
SITE Newcastle, Wyo. (No. 1, SH 16) BORING U-2 SAMPLE No. 1 DEPTH 3.0-5.2 ft



SOIL SUCTION VERSUS WATER CONTENT

SITE Newcastle, Wyo. (No. 1, SH 16) BORING U-2

SAMPLE No. 1 DEPTH 3.0-5.2 ft



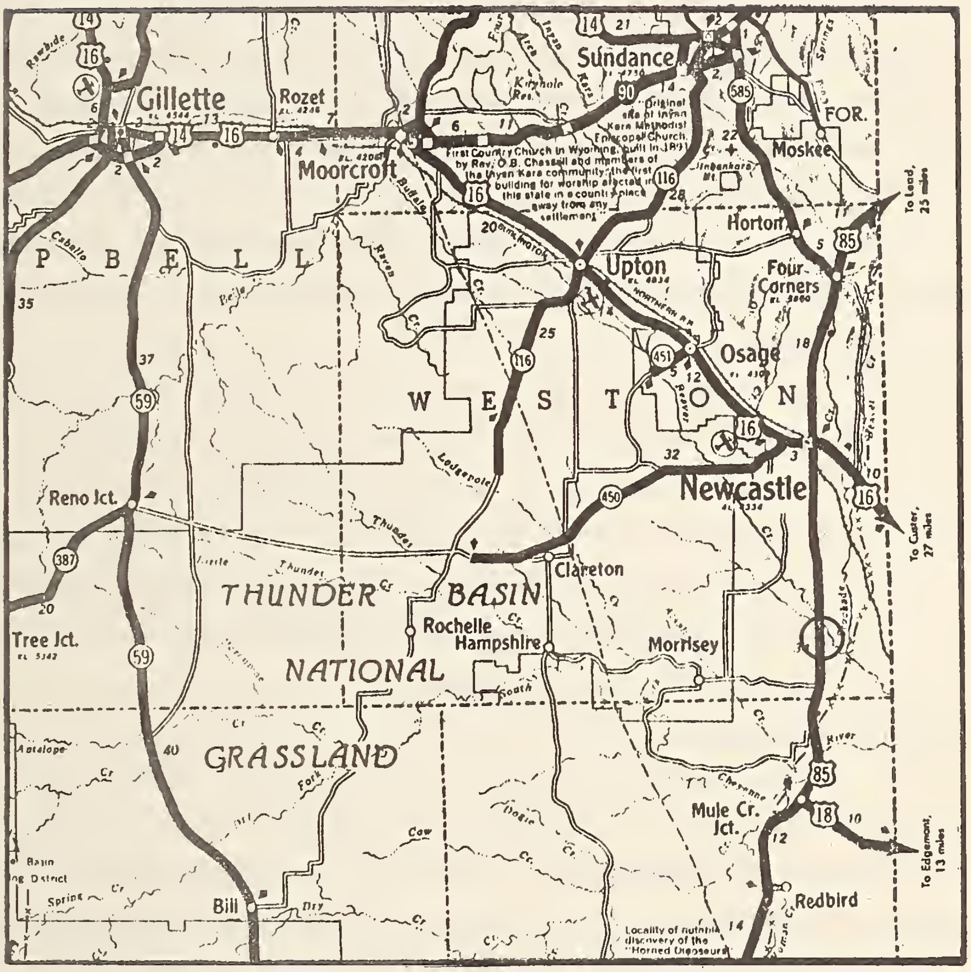
a. Normal to Y, ×650 and ×2300

10 μm　　　b. Normal to X, ×650 and ×2300　　　10 μm

SITE Newcastle, Wyo. (No. 1, SH 16) BORING U-2

SAMPLE No. 1 DEPTH 3.0-5.2 ft

SAMPLING SITE NO. 18, NEWCASTLE, WYO.
(No. 2, U. S. 85)



Site Location Information

210. Sampling site No. 18 is located in northeastern Wyoming approximately 18.5 miles south of Newcastle, Wyo. The site is located approximately 5.5 miles north of Weston-Niobrara County line on U. S. 85. Samples were taken approximately 90 ft east of the centerline of U. S. 85 near milepost 210.

Site Description

211. Sampling site is located at grade in open, flat to gently rolling terrain. Drainage is in a northeasterly direction on a gentle

slope. Surrounding area has a sparse grass cover and no trees.

Site Geology

212. Sampling site is located near the boundary between the Black Hills and the Unglaciated Missouri Plateau Sections of the Great Plains Physiographic Province. Samples were taken in the Pierre Formation of the Montana Group, Gulfian or Upper Series, Cretaceous System. The Pierre Formation consists of over 2000 ft of dark gray shale, sandy shale, sandstone, and bentonite. The Pierre overlies the Niobrara Formation and underlies the Fox Hills or Lewis Formations. The Pierre outcrops in a relatively wide band around the Black Hills Uplift.

Sample Description

213. The Pierre Formation as sampled near Newcastle, Wyoming, is a hard, indurated, weathered, noncalcareous light olive gray (5 Y 6/1) to olive gray (5 Y 4/1) clay shale. Microlaminations are visible in some samples at high magnifications (binocular microscope) but weathering has destroyed most indications of bedding. Mica is a common accessary mineral. The SEM photographs indicate a well-developed, face-to-face particle orientation with some microvoids.

Description of Climate

214. Like the other States in the western part of the country, precipitation varies considerably from one location to another. The period of maximum precipitation occurs in the spring and early summer for most of the State. It is greater over the mountain ranges and usually at the higher elevations, although elevation alone is not the only influence. For example, over most of the southwest portion, where the elevation ranges from about 6500 to 8500 ft above sea level, annual precipitation values vary from 7 to 10 in., while at much lower elevations over the northeast portion and along the east border, where elevations are mostly in the range from 4000 to 5500 ft, annual averages are generally from 12 to 16 in. The relatively dry southwest portion is a high plateau nearly surrounded by mountain ranges.

215. The Big Horn Basin provides a striking example of the effect of mountain ranges in blocking the flow of moisture laden air from the east as well as from the west. The lower portion of the Basin has an

annual precipitation in the range of 5 to 8 in., and it is the driest part of the State. The station showing the least amount is Denver at 4105 ft with an annual mean of only 5.31 in. In the southern part of the Basin, Worland at 4061 ft has an annual mean of 8.15 in. as compared with Termopolis at 4313 ft and 11.15 in. There is another good example in the southeastern part of the State where Laramie at 7236 ft has an annual mean of 11.16 in., while 30 miles to the west, Centennial at 8074 ft received 16.47 in.

216. Snow falls frequently from November through May. Generally, snowfall at lower elevations is light to moderate. About five times a year on the average, stations at the lower elevations will have snowfall exceeding 5 in. Falls of 10 to 15 in. or more for any one storm are occasional but infrequent outside of the mountains. Of course, wind will frequently accompany or follow a snowstorm and pile the snow into drifts several feet deep. Frequently the snow drifts so much that it is difficult to obtain an accurate measurement of snowfall.

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222. Wind is an important factor of the Wyoming climate. This is largely due to the high elevation and enormous stretches of rolling plains. Over the higher south portion, average annual wind speeds range from 12 to 14 mph. Much of the north portion, being considerably lower in elevation has a lower average speed. There are some favorable locations which are protected from the wind by mountain ranges. Lander is one such place and has an annual average of only 7.0 mph at the airport station. The records for the city of Lander show even lighter winds. The lower portion of the Big Horn Basin at such places as Worland and Basin also has very light winds. However, most of Wyoming is quite windy, and during the colder months from November through March there are frequent periods when the wind reaches 30 to 40 mph with occasional

gusts much higher. Prevailing directions in the different localities vary from west-southwest through west to northwest. In many localities winds are so strong and constant from those directions that trees show a definite lean toward the east or southeast.

223. The average relative humidity is quite low and, while this has a distinct advantage in providing delightful summer weather, it is related to the rather low amount of moisture. During the warmer part of the summer days, the average drops to about 25 to 30 percent, and on a few occasions it will be as low as 5 to 10 percent. Late at night when the temperature is lowest the humidity will generally be up to 65 to 75 percent. This results in an average diurnal variation of about 40 to 45 percent during the summer, but in the winter the variation is much less. Low relative humidity, high percentage of sunshine, and rather high average winds add their influence in causing a large amount of evaporation. Because of frequent spells of freezing weather before May 1 and after September 30, it is difficult to obtain consistent records of evaporation for more than the 5-month period from May through September. For this period, the average amount of evaporation is approximately 41 in., as determined from evaporation pans at a few selected locations. The overall range is from a little more than 31 in. at Archer and Sheridan Field Station to near 47 in. at Farson and Boysen Dam.

Climatic Data Summary

Reporting Station: Morrisey (48-6450-07)

Mean Monthly Temperature and Normal
Monthly Precipitation for Period 1941-70:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature, °F	23.3	28.1	33.1	45.8	55.7	64.8	74.6	73.3	62.2	50.7	35.7	26.7	47.8
Precipitation, in.	0.32	0.41	0.70	1.61	2.31	2.37	1.52	1.01	0.87	0.66	0.36	0.32	12.46

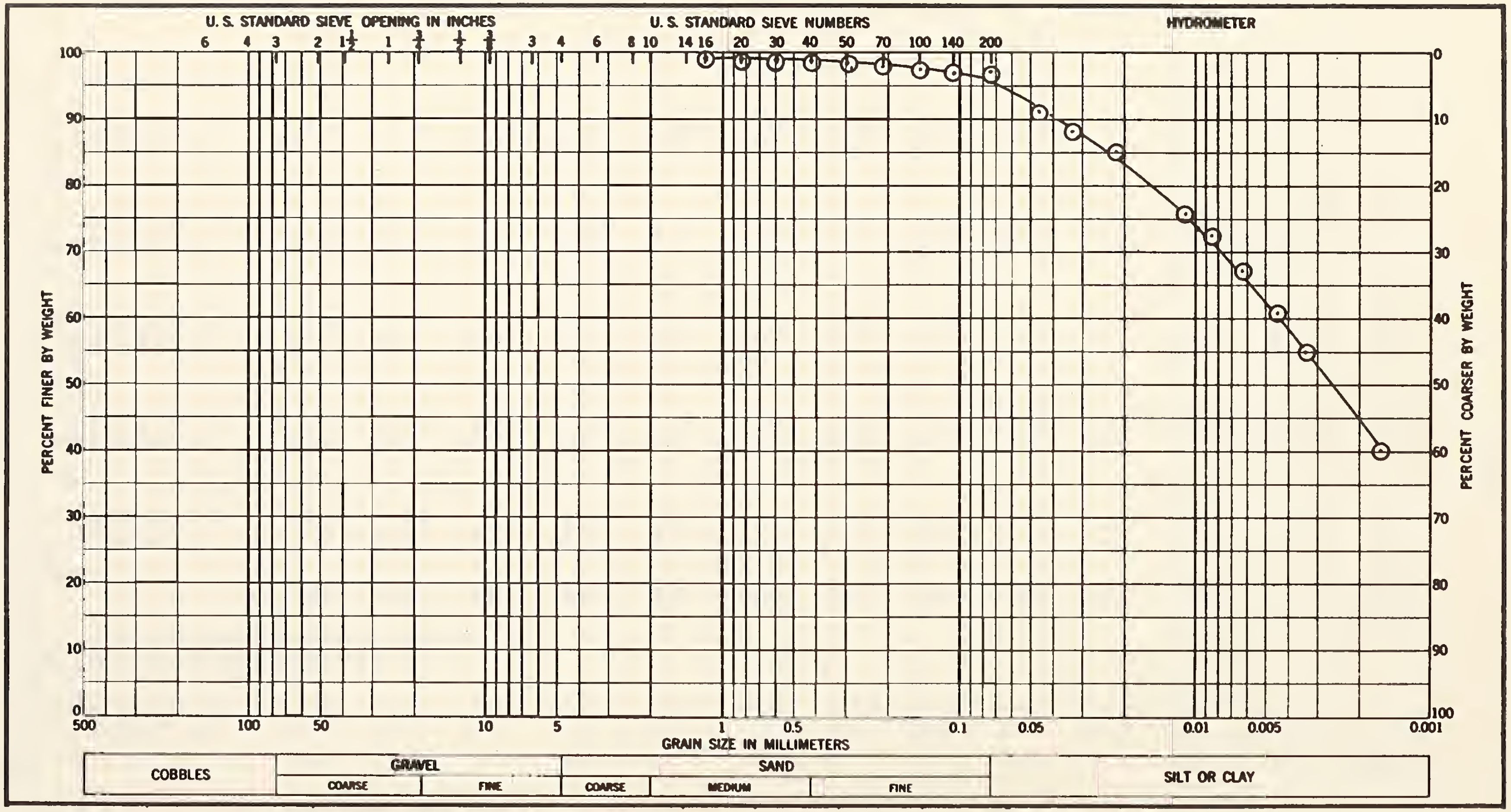
Average Monthly Temperature and
Total Monthly Precipitation for 1971-75:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1971													
Temperature, °F	--*	25.0	33.1	45.3	54.2	67.0	71.3	76.9	5.90	--*	33.9	26.1	--
Precipitation, in.	0.04	0.44	0.51	3.51	3.21	2.34	0.66	0.23	1.48	2.27	0.75	0.07	15.51
1972													
Temperature, °F	16.3	29.0	41.2	45.2	55.8	68.1	69.6	71.1	--*	46.4	31.7	18.6	--
Precipitation, in.	0.40	0.21	0.61	1.36	1.59	2.37	2.64	1.98	0.84	0.35	0.13	0.35	12.83
1973													
Temperature, °F	23.5	29.8	37.9	40.2	55.3	66.6	73.2	74.6	58.1	--*	33.4	26.8	--
Precipitation, in.	0.10	0.17	0.60	3.11	0.46	1.25	3.47	0.90	2.40	1.04	0.62	0.70	14.82
1974													
Temperature, °F	19.3	33.0	38.4	47.6	55.1	69.9	77.6	68.3	60.0	--*	--*	--*	--
Precipitation, in.	0.70	0.00	0.01	1.86	0.73	0.56	1.04	2.02	0.43	1.29	0.25	0.20	9.09
1975													
Temperature, °F	23.2	20.0	29.9	40.6	53.6	62.9	76.8	72.7	--*	50.5	33.9	31.1	--
Precipitation, in.	0.35	0.32	1.36	1.84	2.50	2.84	2.20	0.23	0.08	0.87	0.12	0.42	13.13

Thornthwaite Moisture Index:

1970	1971	1972	1973	1974	1975	
-18.29	-7.26	-5.95	-5.96	-22.62	-17.59	Avg = -12.95

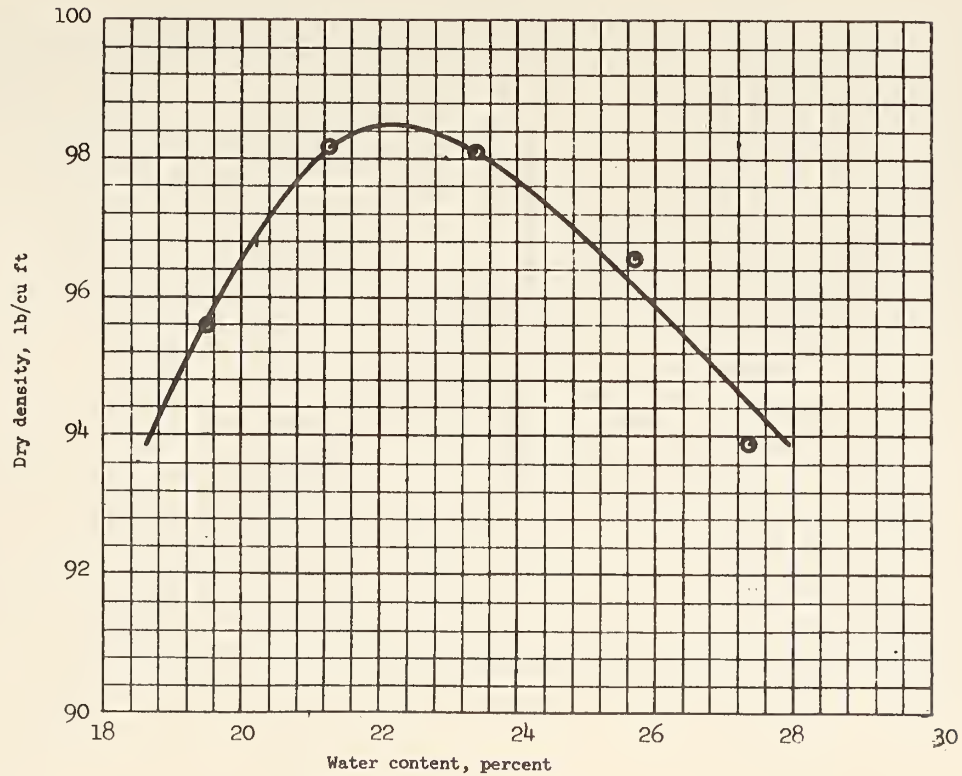
* Record missing.



GRADATION CURVE

SITE Newcastle, Wyo. (No. 2, U. S. 85) BORING U-2

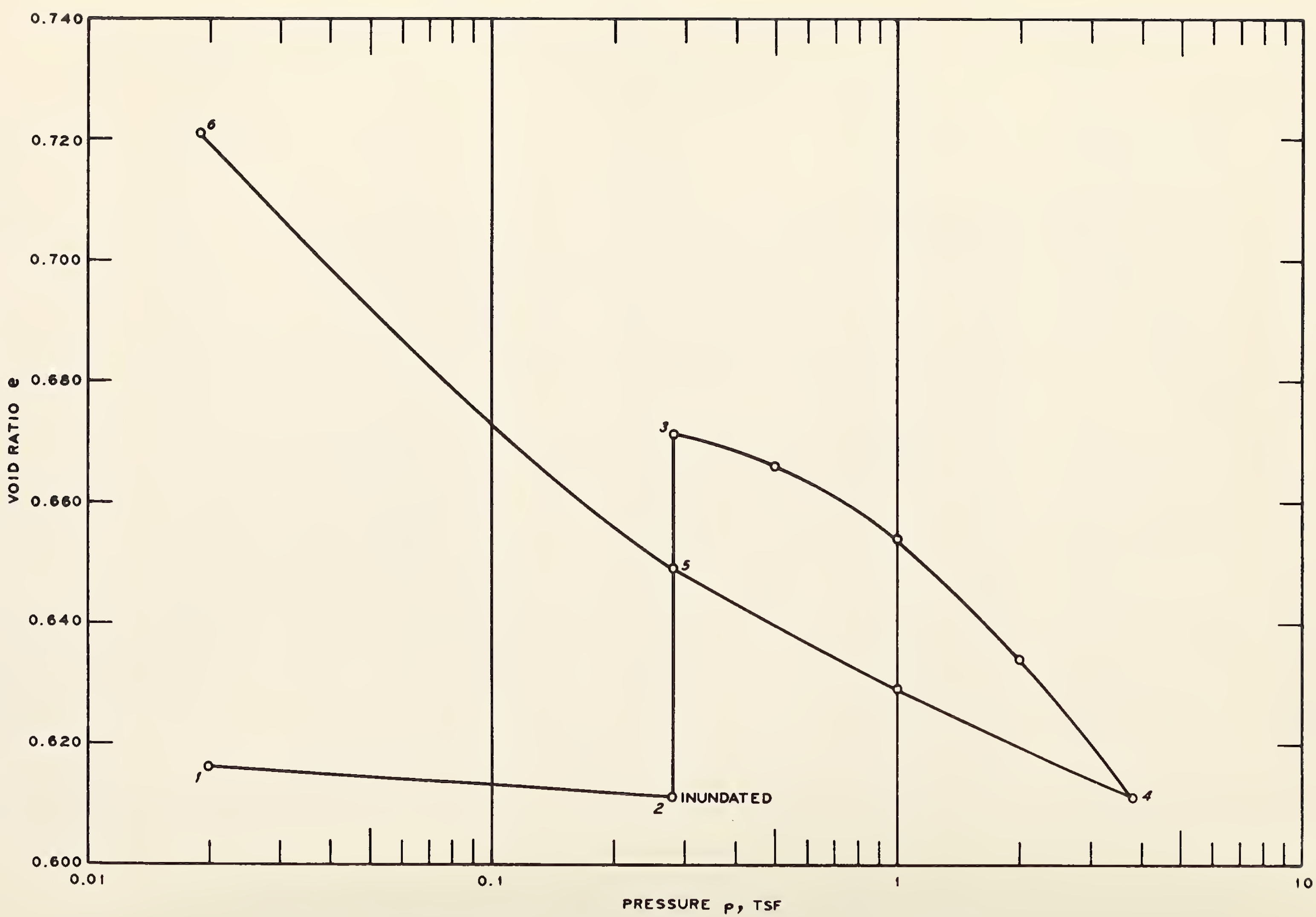
SAMPLE No. 1 DEPTH 1.6-3.8 ft



COMPACTION CURVE

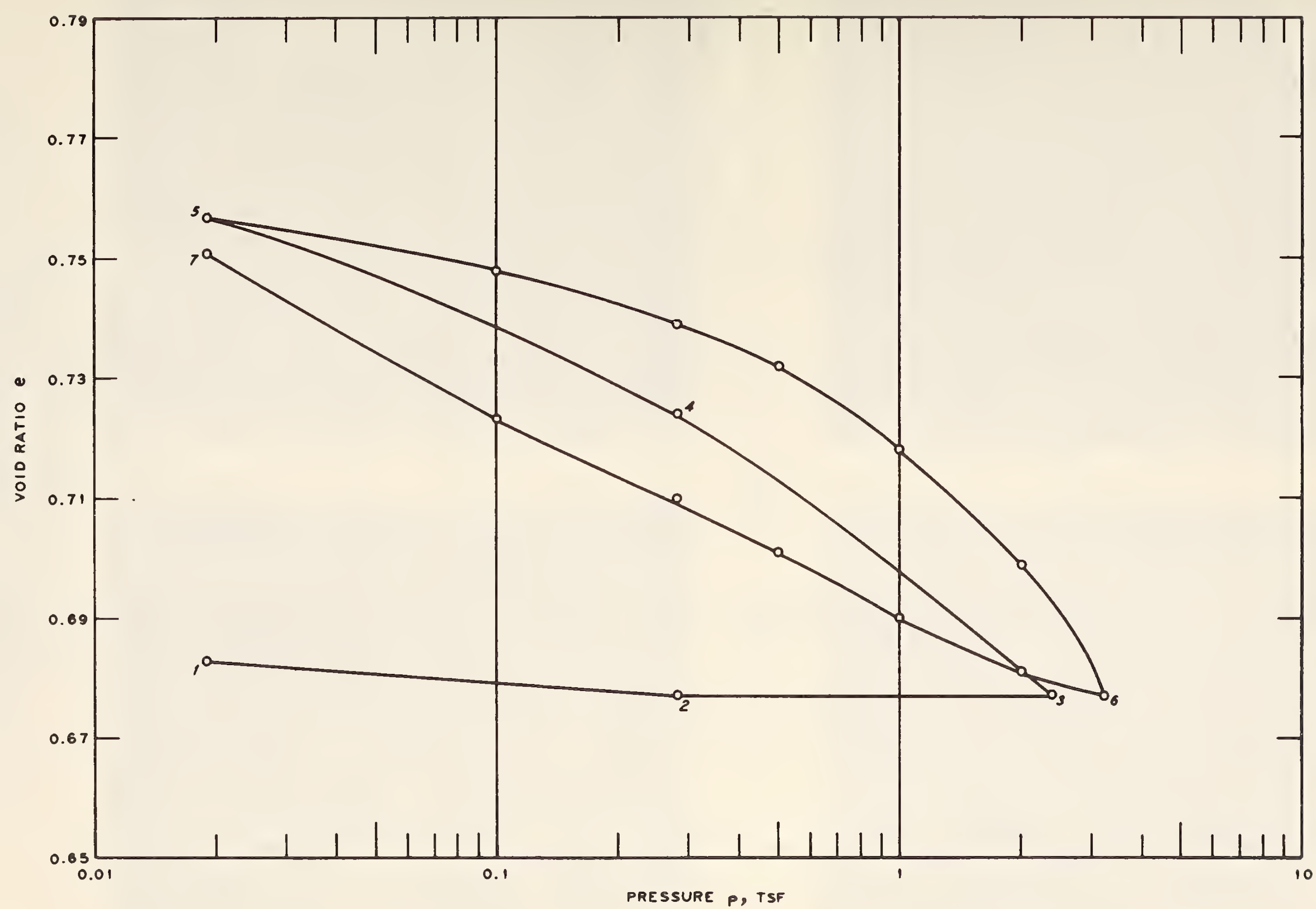
SITE Newcastle, Wyo. (No. 2, U. S. 85)

SAMPLE Disturbed



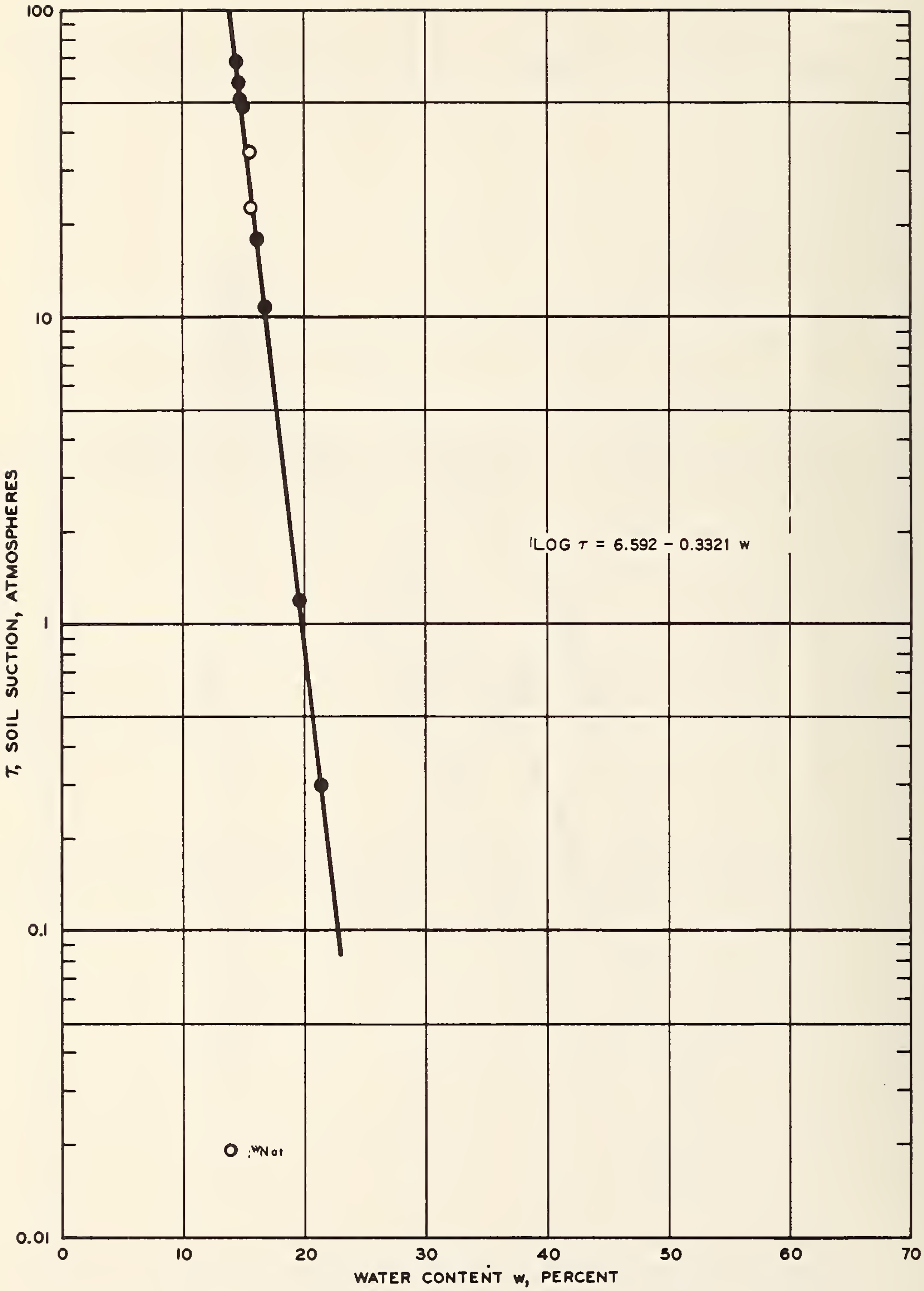
OVERBURDEN SWELL TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

SITE Newcastle, Wyo. (No. 2, U. S. 85) BORING U-2 SAMPLE No. 1 DEPTH 1.6-3.8 ft



CONSTANT VOLUME SWELL PRESSURE TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

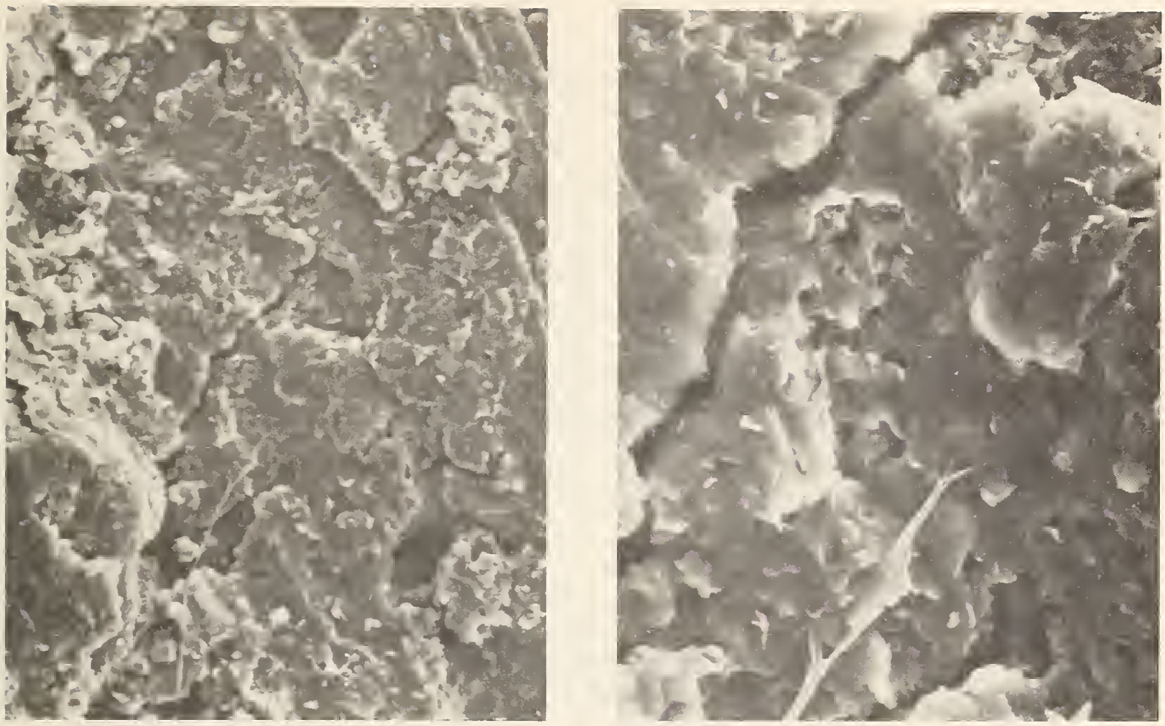
SITE Newcastle, Wyo. (No. 2, U. S. 85) BORING U-2 SAMPLE No. 1 DEPTH 1.6-3.8 ft



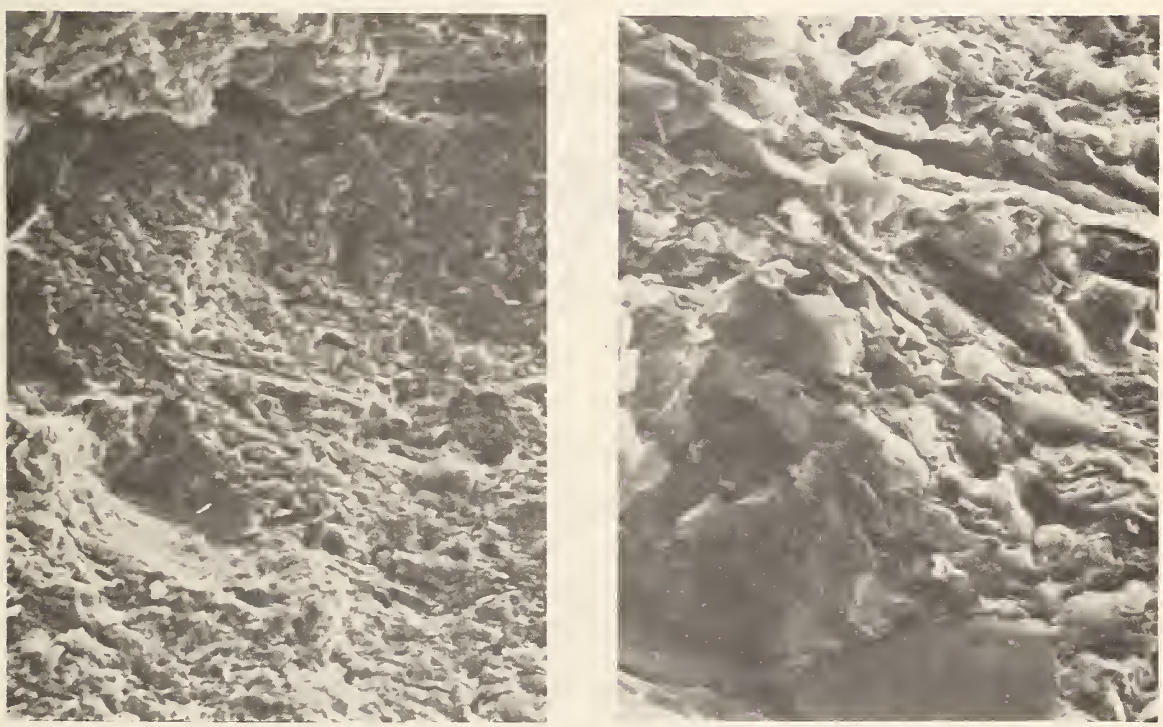
SOIL SUCTION VERSUS WATER CONTENT

SITE Newcastle, Wyo. (No. 2, U. S. 85) BORING U-2

SAMPLE No. 1 DEPTH 1.6-3.8 ft



a. Normal to Y, ×650 and ×2300



10 μm

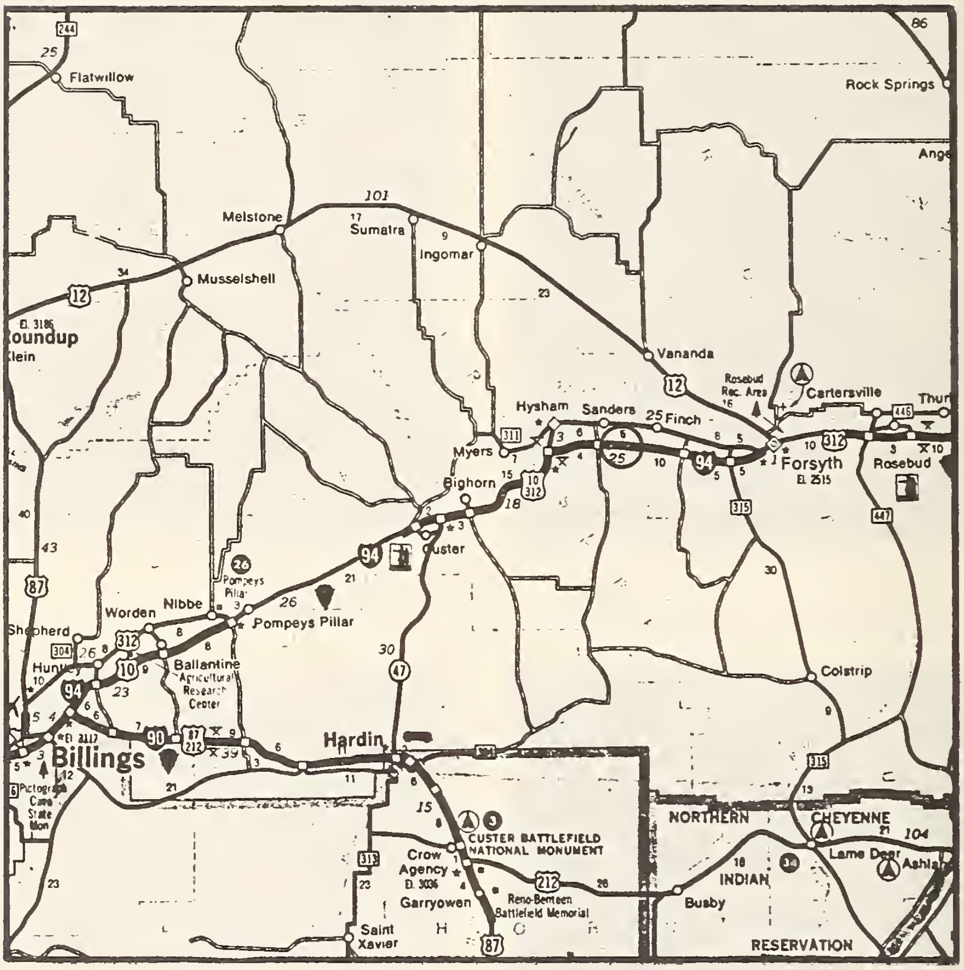
b. Normal to X, ×650 and ×2300

10 μm

SITE Newcastle, Wyo. (No. 2, U. S. 85) BORING U-2

SAMPLE No. 1 DEPTH 1.6-3.8 ft

SAMPLING SITE NO. 19, BILLINGS, MONT.



Site Location Information

224. Sampling site No. 19 is located in southeastern Montana approximately 72 miles northeast of Billings, Mont. The site is located approximately 5 miles east of Hyaham Interchange and approximately 1.5 miles east of Sarpy Creek interchange on I-94. Samples were taken from north verge slope (≈18 ft north of centerline) of eastbound lane at station 1105+00. The area is a cut section in the northeast corner of section 20, T6N, R37E.

Site Description

225. Sampling site is located in a cut section (depth varies

from zero to $\approx$50 to 60 ft) in rolling to hilly terrain. Drainage is in a westerly direction on a moderate slope. Surrounding area has a full grass cover and no trees.

Site Geology

226. Sampling site is located in the Unglaciated Missouri Plateau Section of the Great Plains Physiographic Province. Samples were taken in the Bearpaw Formation of the Montana Group, Upper Series, Cretaceous System. The Bearpaw predominantly consists of shale and silty shale with sandstone and bentonite. The Bearpaw is several hundred feet thick in eastern Montana and is the approximate time equivalent of the Pierre Formation in the Dakotas, Wyoming, and Colorado.

Sample Description

227. The Bearpaw Formation as sampled is a hard, indurated, slightly weathered, noncalcareous, medium gray (N5) silty clay shale. Bedding planes are distinct and frequently voids occur in fragment surfaces. Some fractures are evident in the disturbed samples. Biotite and possibly muscovite are abundant accessary minerals. Yellowish colored iron oxide streaks and pods occuring on relative fresh surfaces indicate some internal alteration or weathering. Clusters of gypsum crystals appear on some of the more weathered surfaces. The SEM photographs indicate a reasonably well-developed face-to-face particle orientation with wavey stratification and considerable nonclay mineral constitutents.

Description of Climate

228. Montana, with an area of 146,316 square miles, is the fourth largest State of the Union. Climatic variations are large. The half of the State southwest of a line from the southeastern corner to the Canadian Border north of Cut Bank in Glacier County is very mountainous, while the northeastern half is very much like Great Plains country, broken occasionally by wide valleys and isolated groups of hills. The extent of the climatic variations one should expect is indicated by the range in elevation of from 1,800 ft above sea level where the Kootenai River enters Idaho to 12,850 ft at Granite Peak near Yellowstone Park. Half the State lies over 4,000 ft above sea level.

229. The Continental Divide exerts a marked influence on the climate of adjacent areas. West of the Divide the climate might be termed a modified north Pacific coast type, while to the east, climatic characteristics are decidedly continental. On the west of the mountain barrier, winters are milder, precipitation is more evenly distributed throughout the year, summers are cooler in general, and winds are lighter than on the eastern side. There is more cloudiness in the west in all seasons, humidity runs a bit higher, and the growing season is shorter than in the eastern plains areas.

230. During the summer months, hot weather occurs fairly often in the eastern parts of the State. The highest ever observed was 117°F at Glendive on July 20, 1893, and Medicine Lake on July 5, 1937. Temperatures of over 100°F sometime occur in the lower elevation areas west of the Divide during the summer, but hot spells are less frequent and of shorter duration than in the plains sections. Hot spells nowhere become oppressive, however, because summer nights almost invariably are cool and pleasant. In the areas with elevations above 4000 ft, extremely hot weather is almost unknown. Summer days, however, are usually warm enough for light summer clothing.

231. In July, the warmest month, temperature averages range from 72.6°F for the Southeastern Division to 64.1°F for the Southwestern Division. This midsummer warmth is fairly steady, very seldom severe, and is tempered by normal nighttime minima in the 50's and 60's.

232. Winters, while usually cold, have few extended cold spells. Between cold waves there are periods sometimes longer than 10 days of mild but often windy weather. These warm, windy winter periods occur almost entirely along the eastern slopes of the Divide and are popularly known as "Chinook" weather. The so-called "Chinook" belt extends from the Browning-Shelby area southeastward to the Yellowstone Valley above Billings. Through this belt, "Chinook" winds frequently reach speeds of 25 to 50 mph or more and can persist, with little interruptions, for several days. In January, the coldest month, temperature averages range from 10.8°F for the Northeastern Division to 22.2°F for the South Central (upper Yellowstone Valley) Division. In some areas east of the

Continental Divide, January or February can average 0°F or below, but such occurrences range from infrequent to about once in 10 to 15 years in the coldest spots.

233. Precipitation varies widely and depends largely upon topographic influences. Areas adjacent to mountain ranges in general are the wettest, although there are a few exceptions where the "rain-shadow" effect appears. Generally, nearly half the annual long-term average total falls in the 3 months, May through July. This is perhaps the main reason why Montana is consistently one of the largest producers annually of dryland grain crops. The Western Division of the State is the wettest and the North Central the driest. There are a few valleys in the Western Division that are relatively dry, as reflected by Deer Lodge and Lonepine averages of 11.00 and 11.46 in., respectively. Probably the driest part of the State is along the Clark Fork of the Yellowstone River in Carbon County. In this area, 8 miles south-southwest of Belfry, the average precipitation for a 16-year period is 6.50 in. The highest average in the State is 34.34 in. at Heron. However, 15 years of records (July-July) from two storage gages at Grinnell Glacier in Glacier National Park, indicate an average annual precipitation of near 120 in. in favorably exposed high mountainous terrain in and near the Park.

234. Annual snowfall varies from quite heavy, 300 in., in some parts of the mountains in the western half of the State, to around 20 in. at some stations in the two northern Divisions east of the Continental Divide. Most of the larger cities have annual snowfall within the 30- to 50-in. range. Most snow falls during the November-March period, but heavy snowstorms can occur as early as mid-September or as late as May 1 in the higher southwestern half of the State. In eastern sections early or late season snows are not very common. Mountain snowpacks in the wetter areas often exceed 100 in. in depth as the annual snow season approaches its end around April 1 to 15.

Climatic Data Summary

Reporting Station: Forsyth 2 E (24-3099-07) for 1941-70
Hysham (24-4358-05) for 1971-75

Mean Monthly Temperature and Normal
Monthly Precipitation for Period 1941-70:

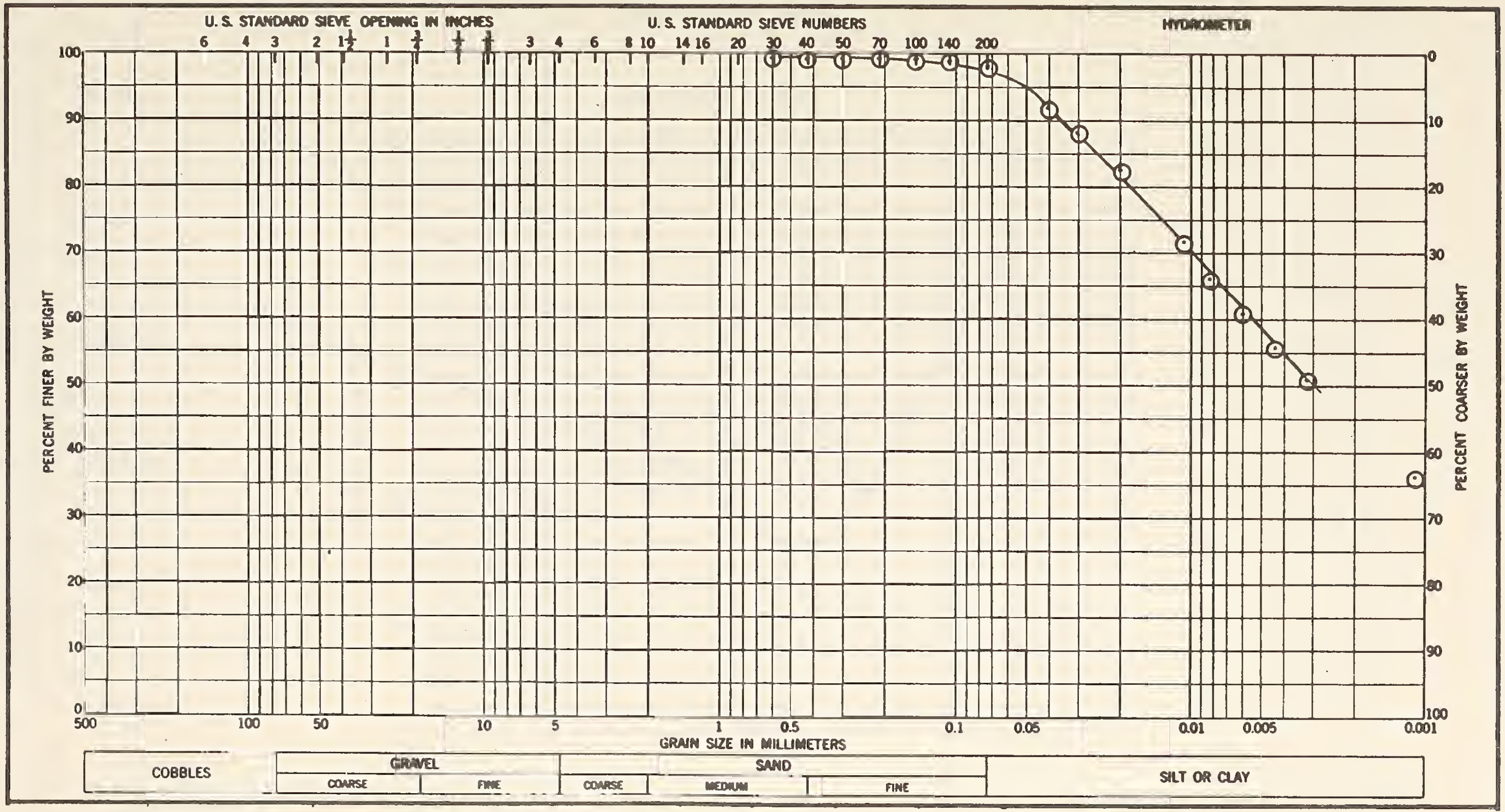
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature, °F	17.3	23.9	31.4	45.5	55.9	63.9	73.1	71.5	59.6	48.6	33.4	23.3	45.6
Precipitation, in.	0.28	0.31	0.50	1.30	1.90	2.97	1.23	1.05	1.06	0.70	0.48	0.35	12.13

Average Monthly Temperature and
Total Monthly Precipitation for 1971-75:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1971													
Temperature, °F	16.7	27.2	34.9	45.6	55.0	65.2	68.8	76.2	57.0	46.8	37.2	17.0	45.6
Precipitation, in.	2.52	0.18	0.60	1.20	1.42	1.70	0.50	1.70	0.79	4.28	0.00	1.01	15.90
1972													
Temperature, °F	12.9	22.6	39.0	45.4	56.9	67.0	67.4	71.1	56.7	45.1	34.2	17.6	44.7
Precipitation, in.	0.65	0.45	0.50	0.74	1.26	0.78	1.54	1.70	0.83	1.47	0.05	0.75	10.72
1973													
Temperature, °F	23.2	29.3	39.5	43.0	55.8	66.0	71.0	73.1	59.7	52.2	30.2	27.4	47.5
Precipitation, in.	0.33	0.15	0.82	2.84	1.34	1.48	0.00	0.80	2.54	0.86	0.49	0.48	12.13
1974													
Temperature, °F	22.2	35.1	38.4	50.3	52.5	67.0	74.1	65.6	57.8	52.3	37.0	30.1	48.5
Precipitation, in.	0.45	0.40	0.46	2.06	3.64	1.76	1.08	1.50	0.66	1.10	0.30	0.05	13.46
1975													
Temperature, °F	24.8	16.2	32.2	39.7	52.8	62.7	74.4	67.7	58.6	47.2	29.6	24.8	44.2
Precipitation, in.	1.02	0.20	1.52	1.78	4.31	2.40	3.58	0.37	0.44	2.87	1.22	0.41	20.12

Thornthwaite Moisture Index:

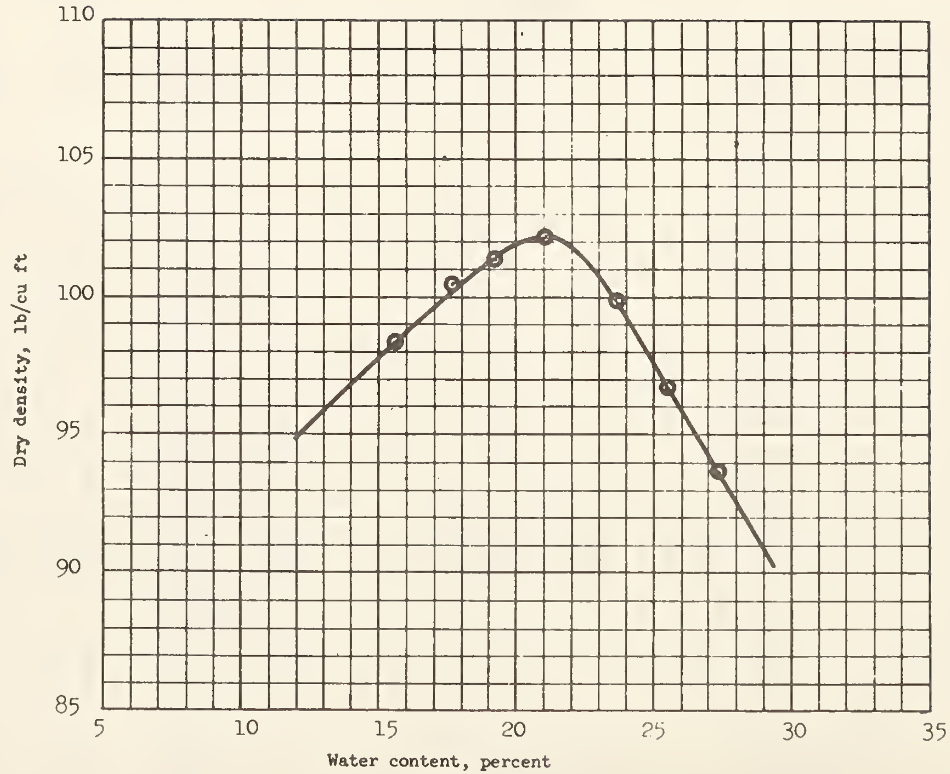
1970	1971	1972	1973	1974	1975	
-1.56	-7.93	-0.53	-7.10	-1.88	9.64	Avg = -1.56



GRADATION CURVE

SITE Billings, Mont. BORING U-2

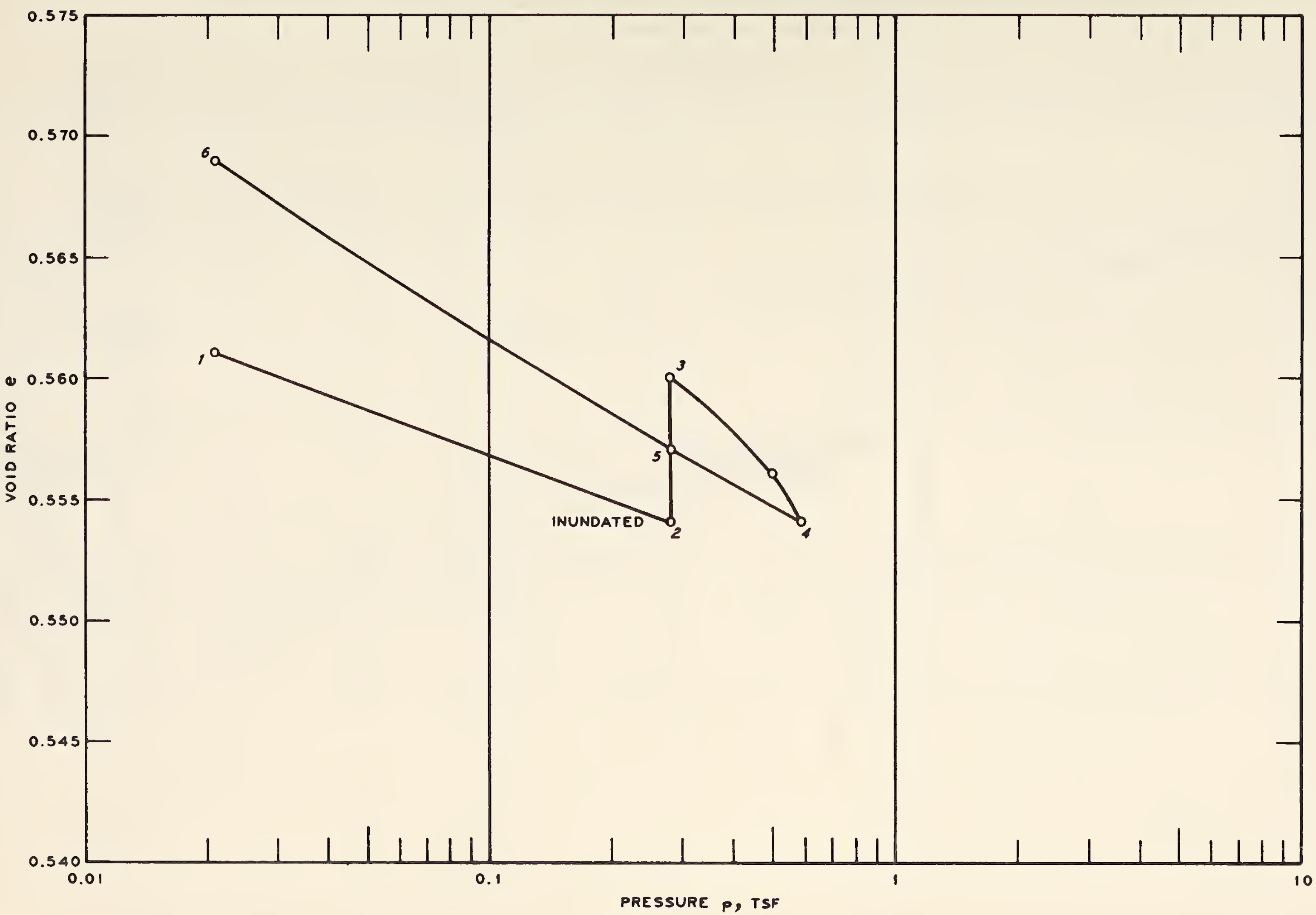
SAMPLE No. 1 DEPTH 3.1-4.6 ft



COMPACTION CURVE

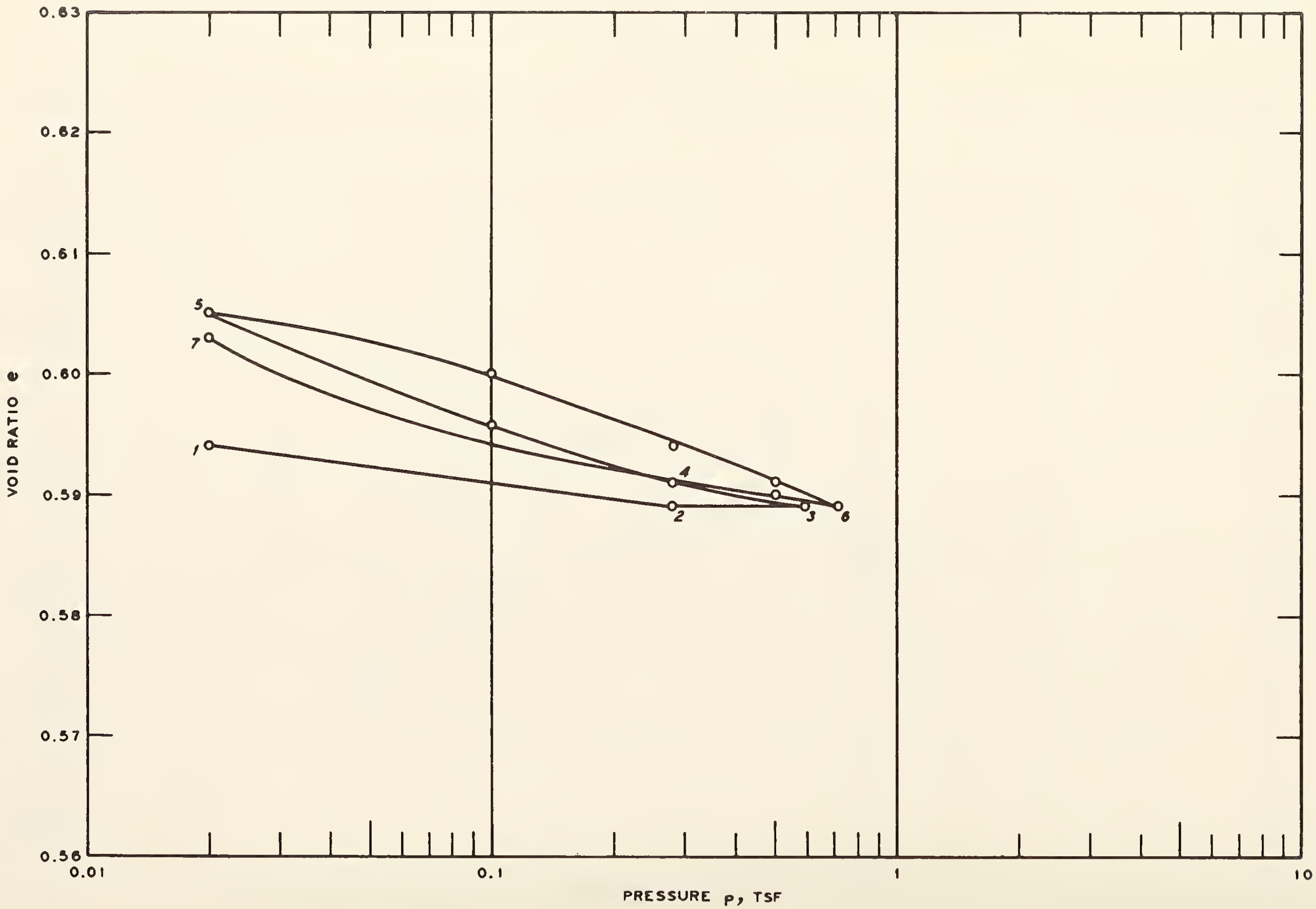
SITE Billings, Mont.

SAMPLE Disturbed



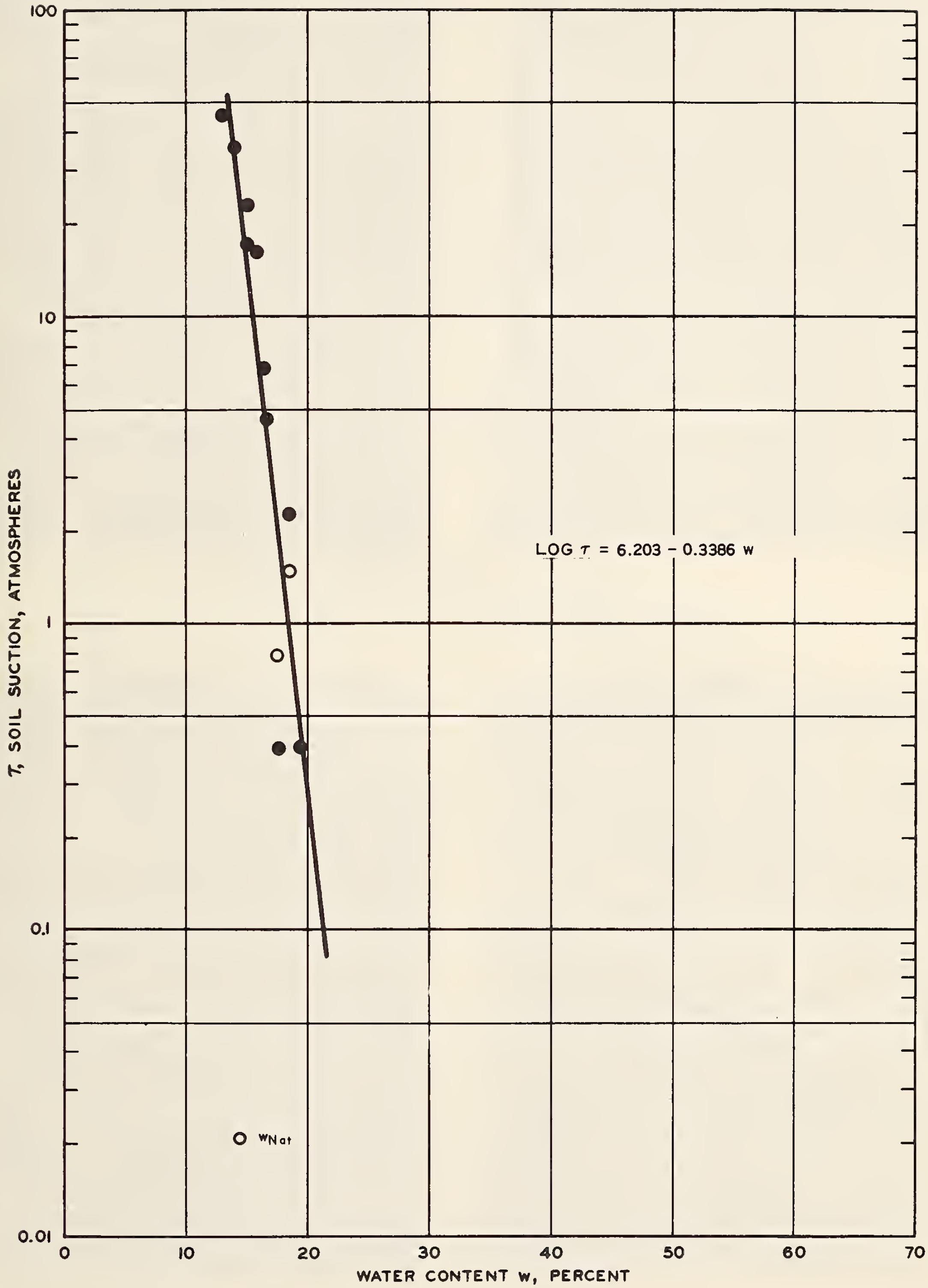
OVERBURDEN SWELL TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

SITE Billings, Mont. BORING U-2 SAMPLE No. 1 DEPTH 3.1-4.6 ft



CONSTANT VOLUME SWELL PRESSURE TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

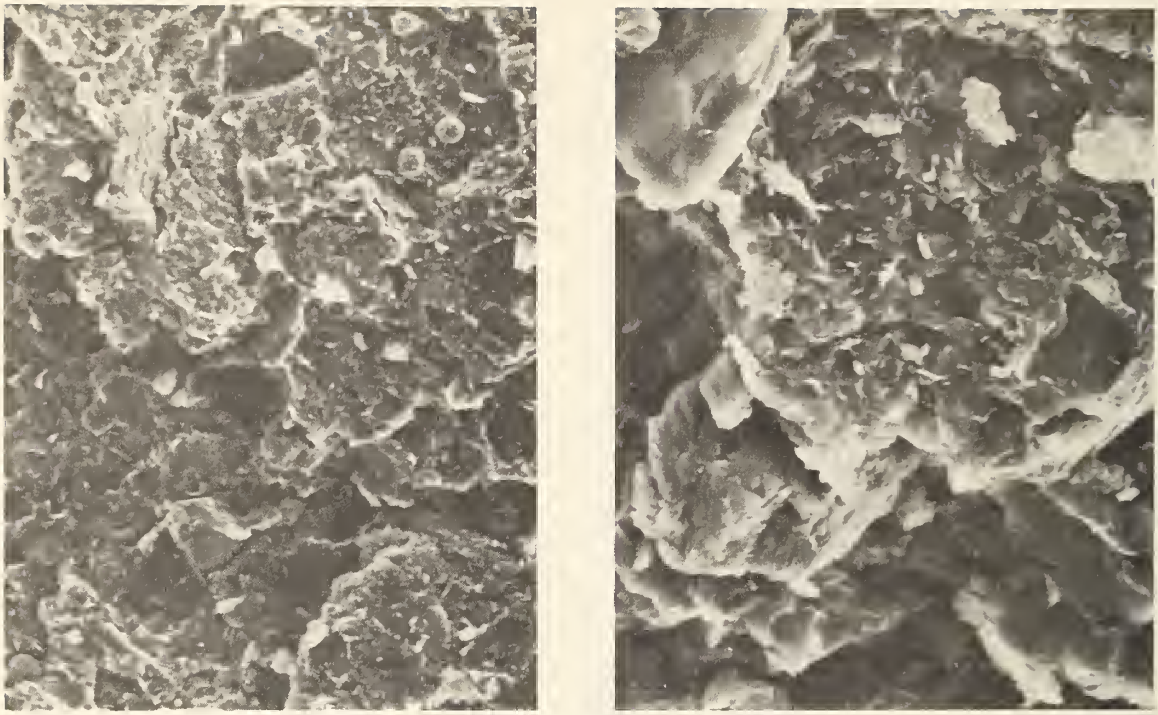
SITE Billings, Mont. BORING U-2 SAMPLE No. 1 DEPTH 3.1-4.6 ft



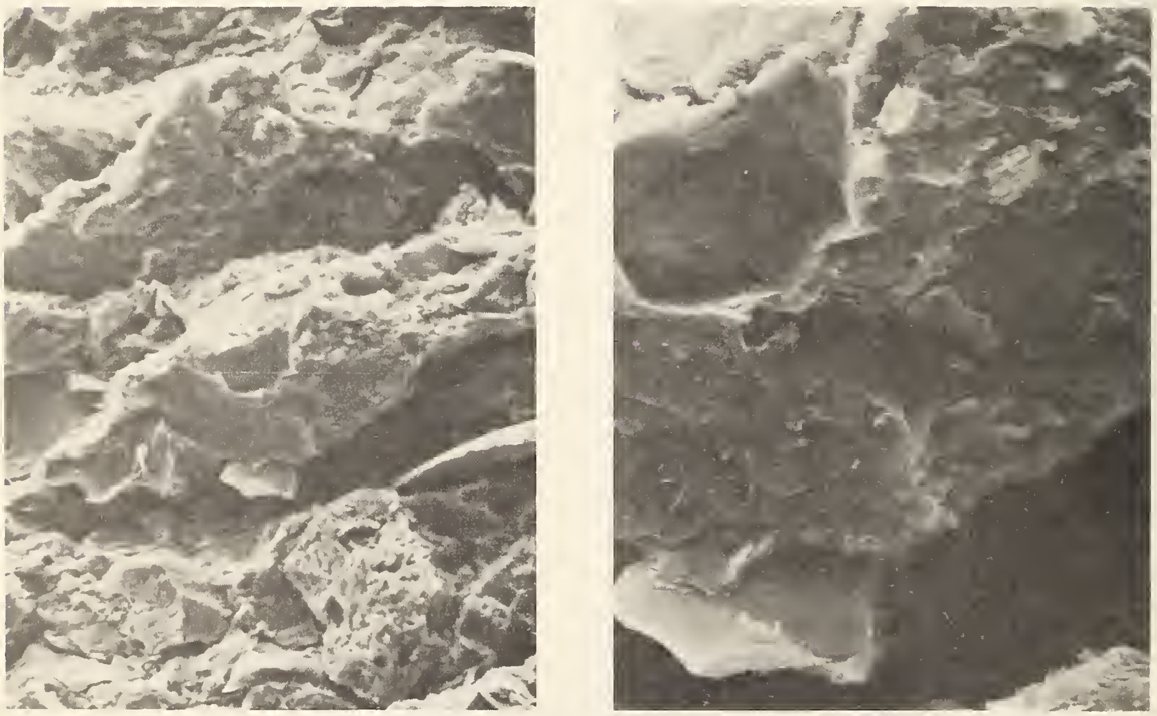
SOIL SUCTION VERSUS WATER CONTENT

SITE Billings, Mont. BORING U-2

SAMPLE No. 1 DEPTH 3.1-4.6 ft



a. Normal to Y, ×650 and ×2300



10 μm

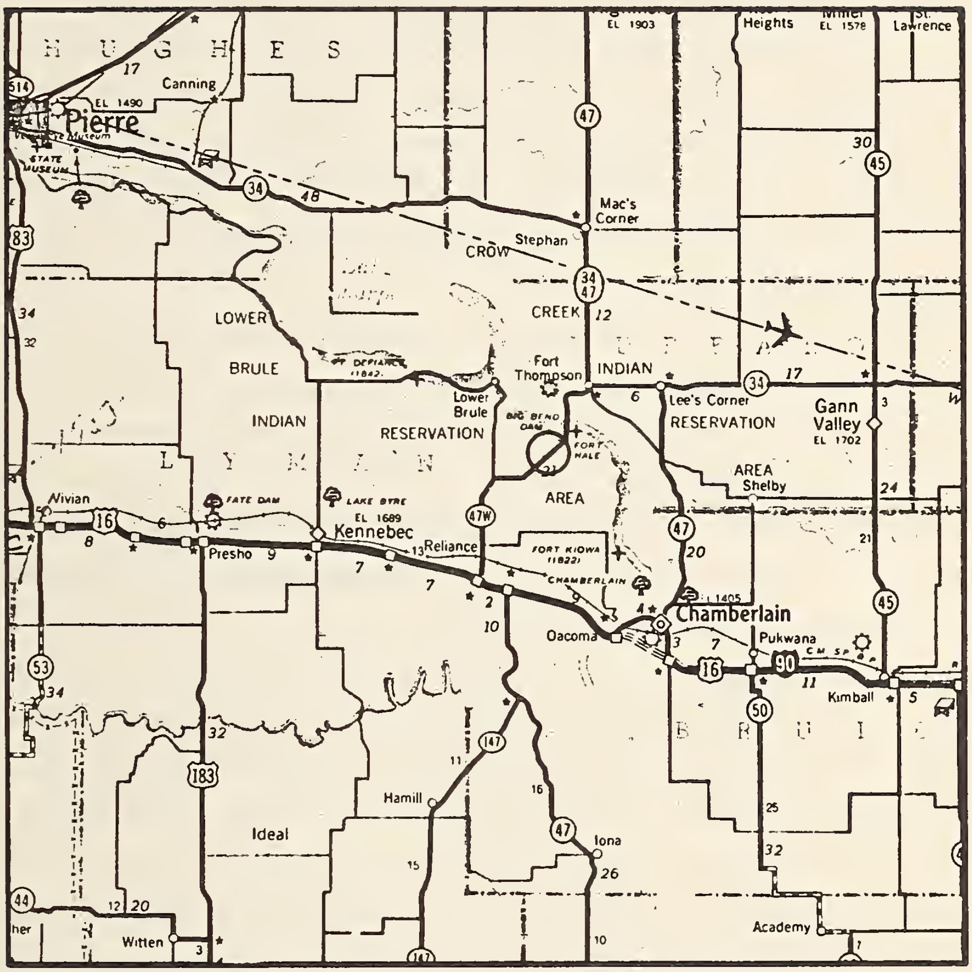
b. Normal to X, ×650 and ×2300

10 μm

SITE Billings, Mont. BORING U-2

SAMPLE No. 1 DEPTH 3.1-4.6 ft

SAMPLING SITE NO. 20, RELIANCE, S. DAK.



Site Location Information

235. Sampling site No. 20 is located in south-central South Dakota (Lyman County) approximately 50 miles southeast of Pierre, S. Dak. The site is located on SH 47W between Big Bend Dam and Reliance, S. Dak. Samples were taken from one of the control areas in the Lyman County test section near station 222+00 (milepost 72.44). Samples taken in right-of-way approximately 210 ft east of centerline.

Site Description

236. Sampling site is located at grade in open, flat to very gently rolling terrain. Drainage is in a northeasterly direction on a

gentle slope. Surrounding area has a full grass cover and no trees.

Site Geology

237. Sampling site is located in the Unglaciated Missouri Plateau Section of the Great Plains Physiographic Province. Samples were taken in the Pierre Formation of the Montana Group, Upper Series, Cretaceous System. The Pierre consists predominantly of shale, sandstone, and bentonite and varies in thickness from 360 to over 1200 ft. It overlies the Niobrara Formation and is overlain by the Fox Hills Formation.

Sample Description

238. The Pierre Formation as sampled near Reliance, S. Dak., is a hard, indurated, weathered, calcareous, medium gray (N5) to dark gray (N3) clay shale. The material is fissile with bedding planes locally characterized by black manganese oxide or yellow iron oxide staining. The SEM photographs indicate a well-developed, face-to-face particle orientation with microvoids and fractures exhibiting some wavey stratifications.

Description of Climate

239. Since South Dakota is situated in the heart of the North American Continent, it has the extremes of summer heat and winter cold that are characteristic of continental climates. Rapid fluctuations in temperature are common. Partly because of the great distance from any large body of water, the ranges of daily, monthly, and annual temperatures are very large. Temperatures of 100°F, or higher, are experienced in some part of the State each summer, and on rare occasions such readings have been noted as early as April and as late as October. These high temperatures are usually attended by low humidity, which greatly reduces the oppressiveness of the heat. Below-zero temperatures occur frequently on midwinter mornings, but it is not often that the temperature stays below zero during the entire day. In the north, subzero temperatures can occur in October and April.

240. Warm, "Chinook" winds and frequent sunny skies make the Black Hills area the warmest part of the State in winter. Also, because of the tendency for very cold air masses to stay at low elevations, some of the arctic air outbreaks that blanket the eastern counties do not

reach the higher counties in the west. During summer, the higher elevation of the Black Hills results in that section having cooler temperatures than the rest of the State. At this season, the central and southeastern counties are warmest. The freeze-free season is shortest high in the Black Hills where brief freezing has been known to occur at any time of summer. Elsewhere, the first autumn freeze generally occurs in mid-September in the northwest, in late September in the central and east, and in the first week of October in the extreme southeastern corner. The average time of the last freeze in spring ranges from early May in the southeast to late May in the northwest.

241. The annual precipitation decreases northwestward from about 25 in. in the extreme southeast to less than 13 in. in part of the northwest. The Black Hills are again an exception, varying from 16 in. in their southern portion to almost 25 in. in the northern, where rain and snow are often formed when the prevailing winds are abruptly forced up the mountainsides. Most of the State's precipitation occurs during the crop season, April through September. On the average, it reaches a maximum during June, and decreases sharply in early July. In the east, there is a small secondary increase in August, followed by an overall diminishing during autumn. The least precipitation is received during winter.

242. Occasionally there is heavy snowfall in winter and the amount of snow on the ground accumulates to a considerable depth, but as a rule, the snow cover is not great. Wind usually accompanies the snow, causing a large proportion of it to collect in gullies and behind windbreaks. In the worst storms, isolated drifts many feet deep may block roads, while windswept fields nearby are nearly bare of snow. Accurate measurements of the snow are difficult, since irregularities are introduced by the presence of buildings, fences, trees, and weeds; and by variations in the terrain, wind, and the snow itself. Snow that falls early in the season seldom stays on the ground very long. After the ground has frozen deeply and the days become very short, it remains longer. Once a snow cover is present, there is a tendency for it to continue, since the temperature falls to much lower levels over snow

than over bare ground. Snowfall reaches a maximum in February and early March, and decreases markedly near the end of March. Violent, cold winds carrying snow picked up from the ground, commonly called "blizzards," are not very frequent and are a hazard only to those who are unprepared for a winter storm.

Climatic Data Summary

Reporting Station: Kennebec (39-4516-06)

Mean Monthly Temperature and Normal
Monthly Precipitation for Period 1941-70:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature, °F	17.2	22.3	31.0	47.3	58.1	67.5	74.9	73.9	62.8	51.2	34.7	22.3	46.9
Precipitation, in.	0.33	0.53	0.83	1.92	2.69	3.53	2.05	2.34	1.52	1.03	0.63	0.37	17.77

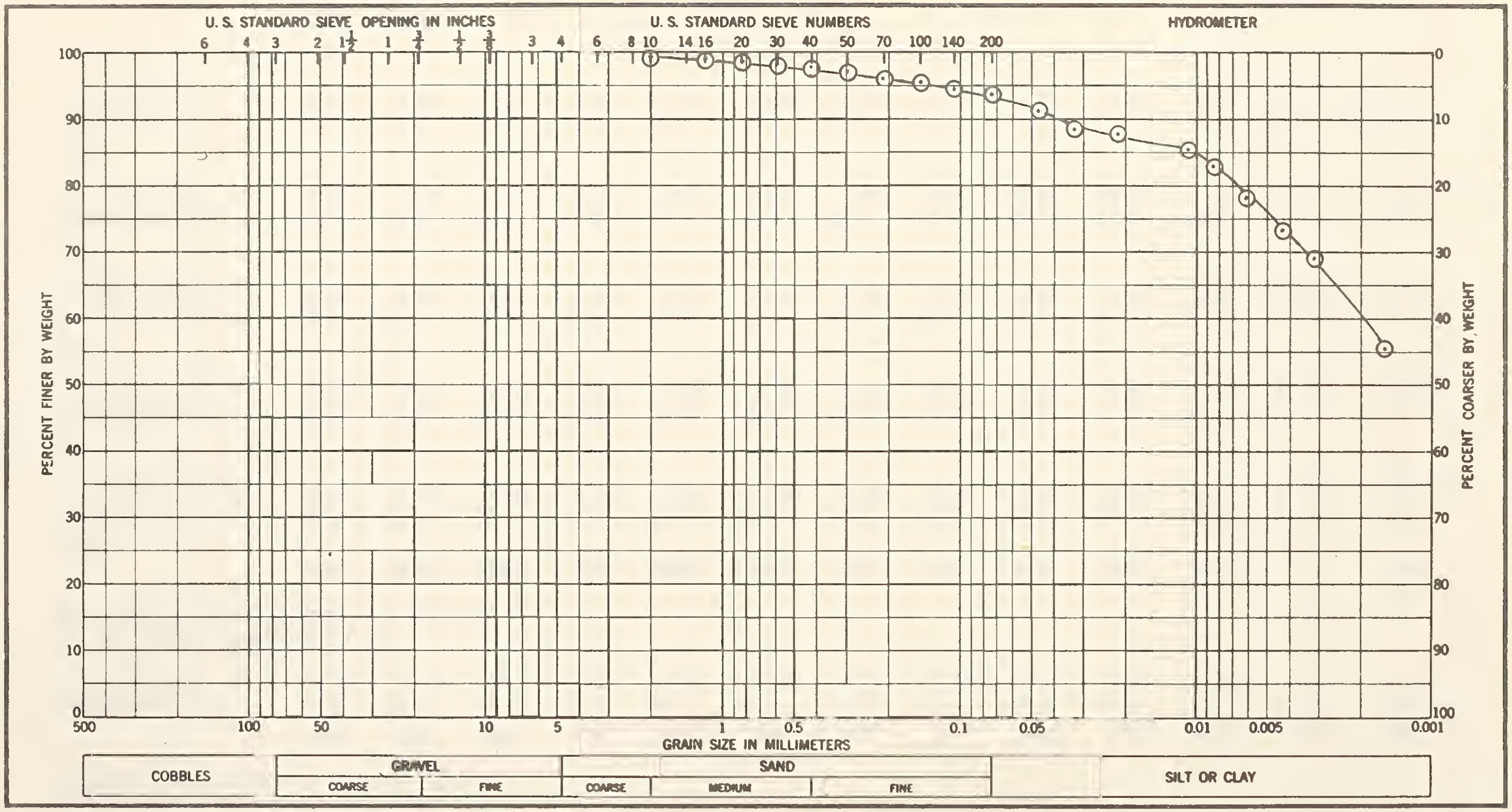
Average Monthly Temperature and
Total Monthly Precipitation for 1971-75:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1971													
Temperature, °F	12.8	20.7	32.2	49.1	57.0	73.6	72.6	77.6	62.8	51.3	34.6	18.9	46.9
Precipitation, in.	0.17	1.03	0.23	3.73	1.82	1.09	0.70	3.62	1.03	2.25	0.64	0.37	16.68
1972													
Temperature, °F	12.5	18.6	35.0	45.7	60.0	68.3	71.3	73.8	65.1	47.7	31.9	16.9	45.6
Precipitation, in.	0.06	0.14	0.37	3.25	3.51	4.06	3.68	0.66	0.09	1.03	1.45	0.70	19.00
1973													
Temperature, °F	21.0	27.2	40.9	46.9	57.9	70.3	76.2	78.8	61.0	54.3	34.1	21.0	49.1
Precipitation, in.	0.50	0.17	2.51	0.79	3.53	1.00	1.33	1.62	2.85	1.59	0.40	0.09	16.38
1974													
Temperature, °F	21.1	28.8	39.2	49.6	57.5	68.3	81.0	71.6	60.8	53.9	35.9	26.3	49.5
Precipitation, in.	0.03	0.06	0.90	3.14	4.55	1.74	3.62	0.44	0.36	0.61	0.03	0.03	15.51
1975													
Temperature, °F	21.2	18.3	29.0	44.3	60.4	69.9	80.4	75.7	61.8	53.6	33.4	25.6	47.8
Precipitation, in.	0.52	0.02	2.03	1.31	0.94	3.69	2.31	3.19	0.86	0.68	0.02	0.28	15.85

Thornthwaite Moisture Index:

1970	1971	1972	1973	1974	1975
-15.20	-10.57	-4.74	-12.27	-24.13	-10.46

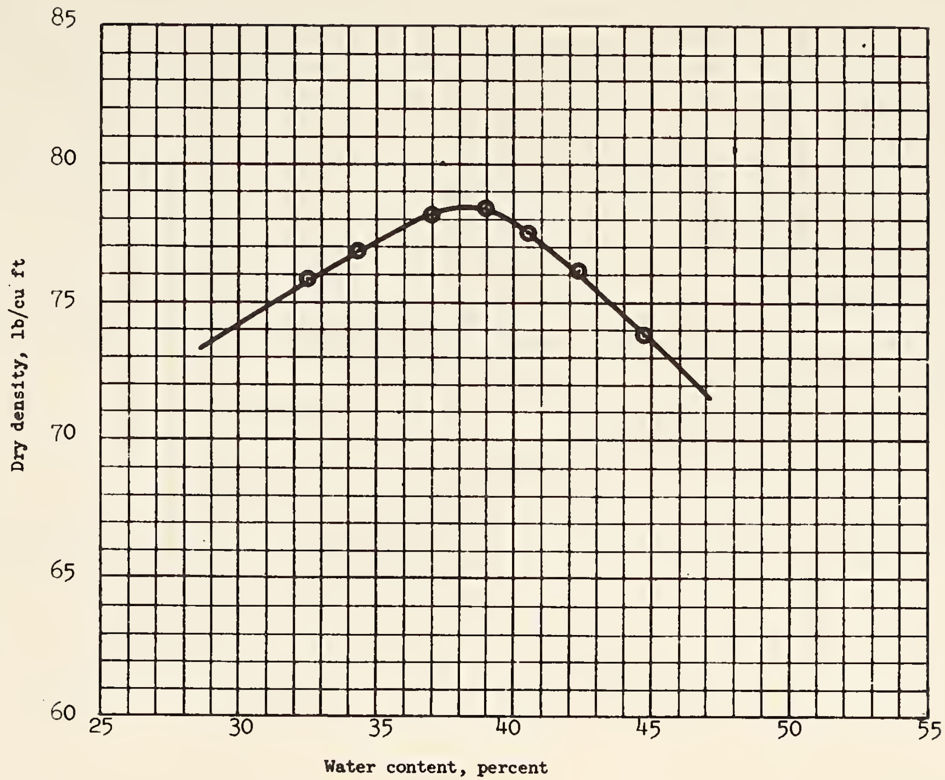
Avg = -12.9



GRADATION CURVE

SITE Reliance, S. Dak. BORING U-2

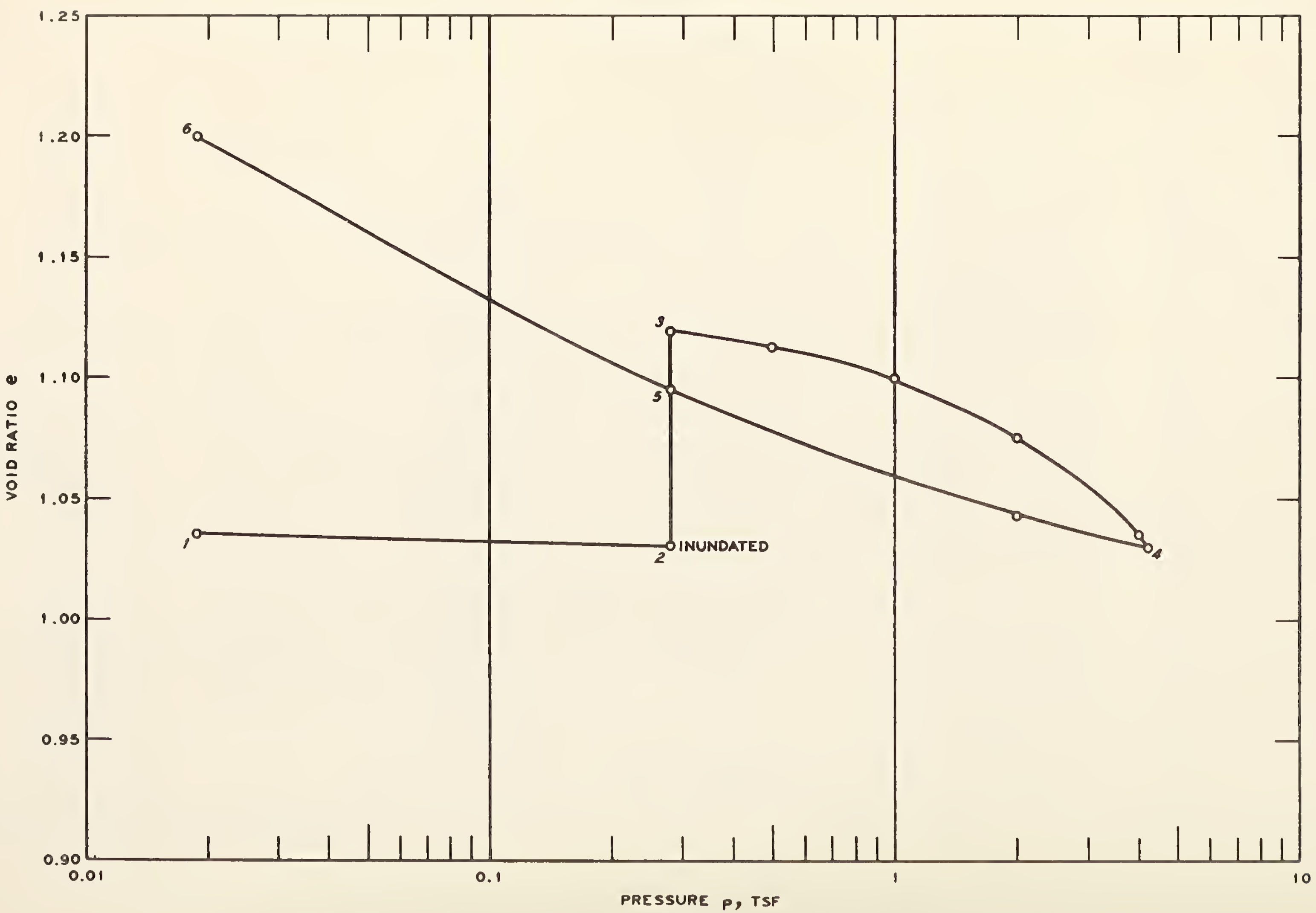
SAMPLE No. 1 DEPTH 1.7-3.9 ft



COMPACTION CURVE

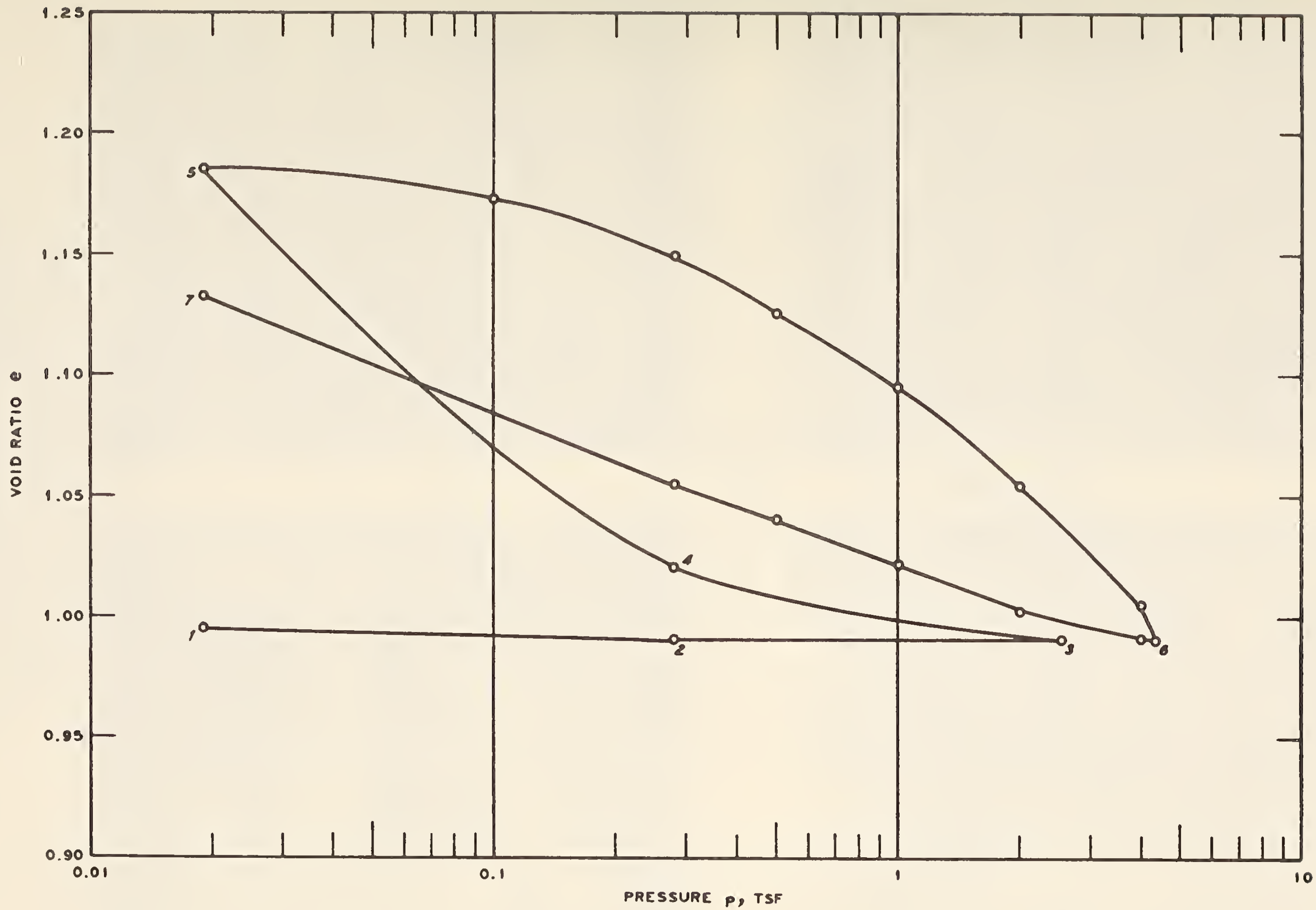
SITE Reliance, S. Dak.

SAMPLE Disturbed



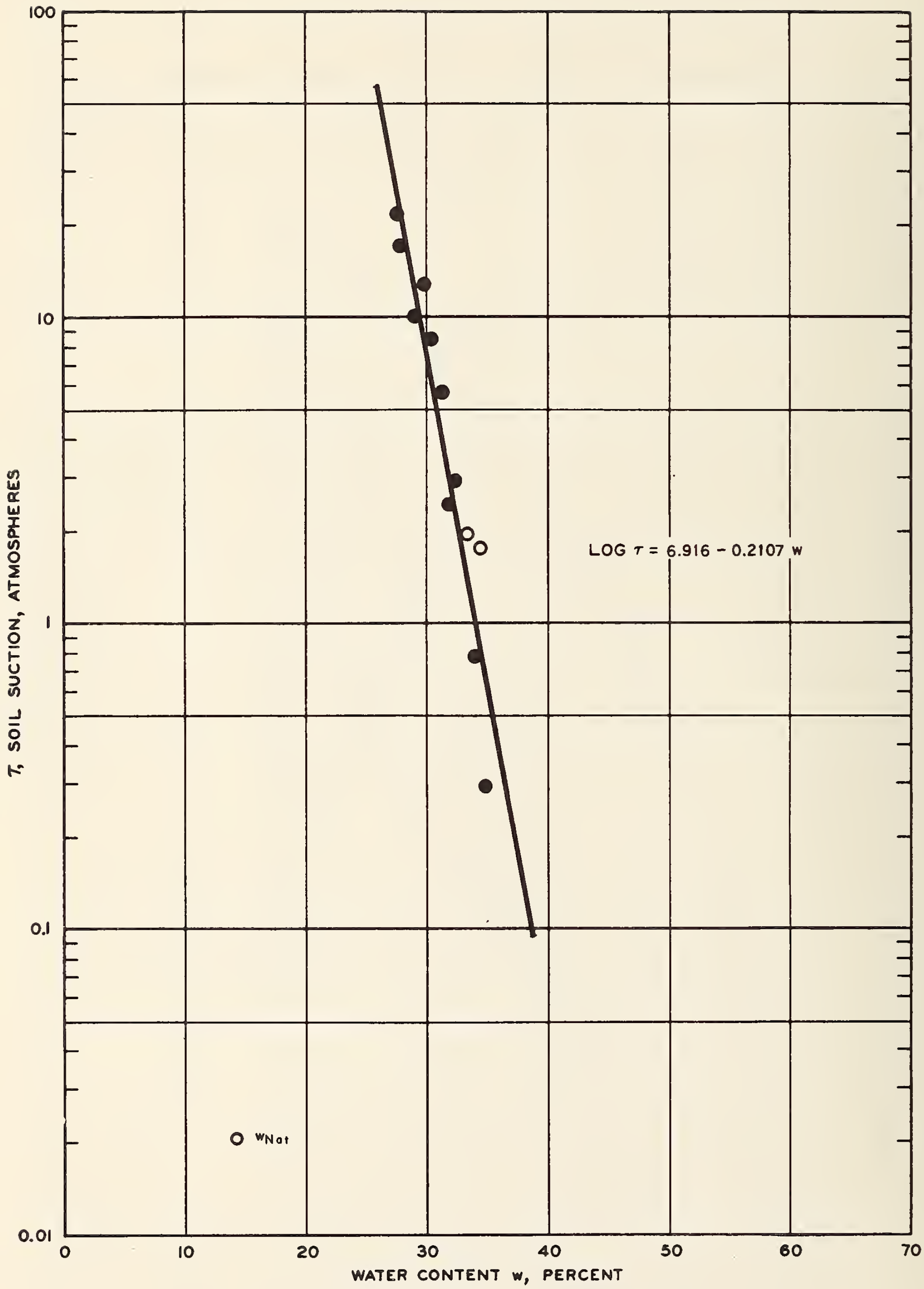
OVERBURDEN SWELL TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

SITE Reliance, S. Dak. BORING U-2 SAMPLE No. 1 DEPTH 1.7-3.9 ft



CONSTANT VOLUME SWELL PRESSURE TEST, VOID RATIO VERSUS LOG PRESSURE CURVE

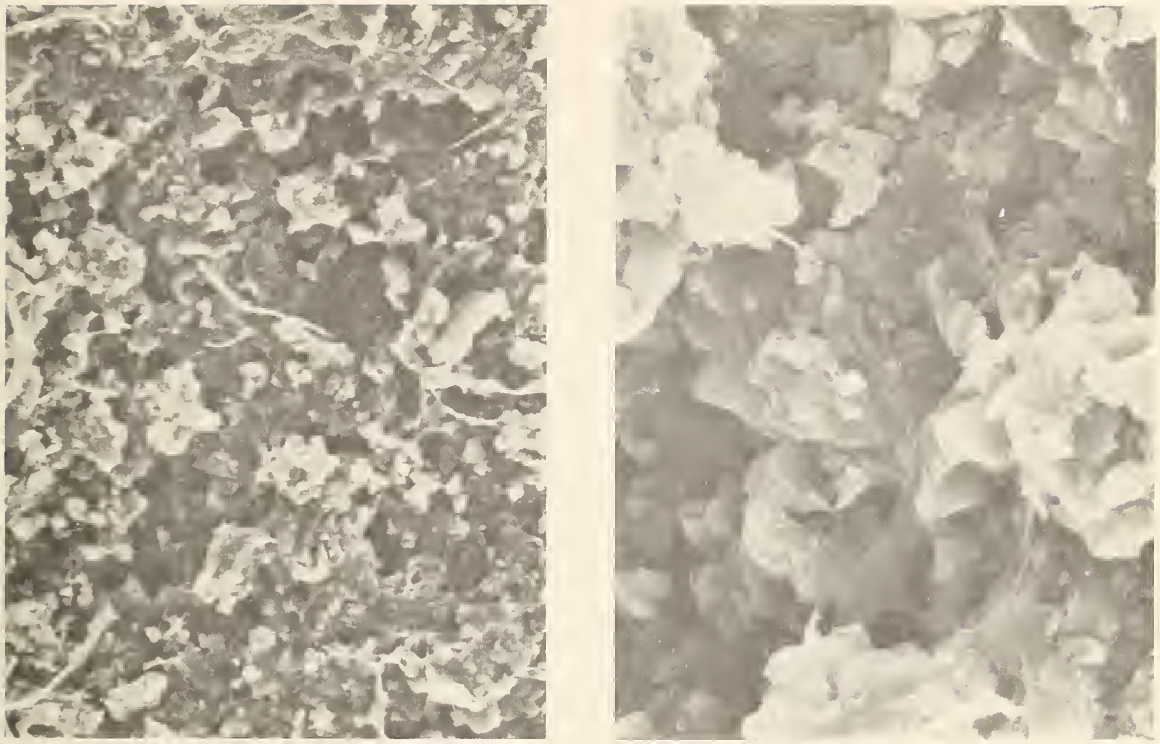
SITE Reliance, S. Dak. BORING U-2 SAMPLE No. 1 DEPTH 1.7-3.9 ft



SOIL SUCTION VERSUS WATER CONTENT

SITE Reliance, S. Dak. BORING U-2

SAMPLE No. 1 DEPTH 1.7-3.9 ft



a. Normal to Y, X650 and X2300

10 μm

b. Normal to X, X650 and X2300

10 μm

SITE Reliance, S. Dak. BORING U-2

SAMPLE No. 1 DEPTH 1.7-3.9 ft

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